A Portable Duplex Radio-Telephone*

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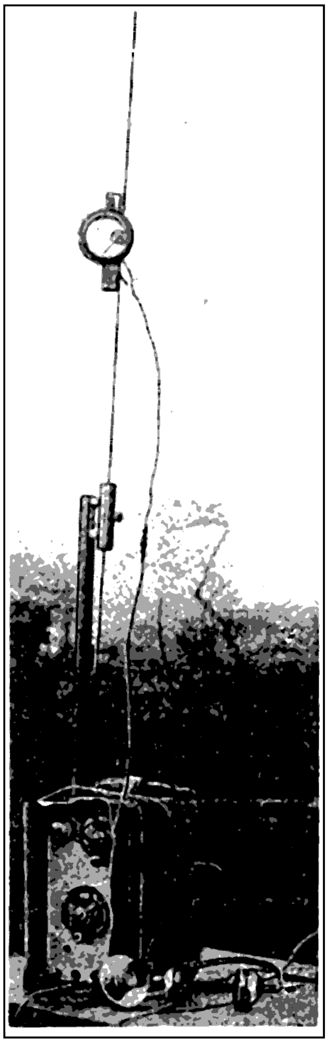
SUMMARY.—A practical system of duplex radio-telephony on ultra-short waves is described in which each set is made alternately transmitter and receiver at a supersonic frequency. The interrupted oscillation provides super-regenerative amplification which is so great that no additional amplification is required, and the sets are therefore simple and may be light in weight. The quench frequency must be selected according to the distance between the sets. Telephony transmission is effected by modulation of the quench oscillator. Since true duplex communication is obtained without appreciable "side tone," one or both sets may be directly connected to an ordinary telephone line.

The theory of the super-regenerative receiver is reviewed and also some practical aspects of the propagation of ultra-short waves.

Attention is directed to the remarkable facility of synchronisation of the quench frequencies even when signals are weak.



The duplex radio-telephone set up ready for use

THE system to be described provides in the strictest sense a duplex radio-telephone; that is to say, conversation may pass in both directions at the same time. No manual or voice-operated switches or cut-outs are employed. Further, the radio-telephone may be directly connected at one or both ends to ordinary line telephone circuits. "Subscribers" on these telephone circuits might well be unaware that any radio link was in use.

Introduction

(a) Other Duplex systems

The great problem of duplex radio-telephony is to prevent the sensitive receiver from being swamped by the local transmitter. Apart from the obvious methods of spacing the receiving apparatus and the transmitting apparatus as far apart as possible, and of using very different wavelengths for the two directions of communication, it appears that two solutions have been put forward. The first is attributed to C. E. Franklin.[1] In this method the local transmitter is made to act as the oscillator of a super-heterodyne receiver, the supersonic beat frequency between this local oscillation and the received signal being then amplified and detected in the usual way. In the second method each apparatus is made alternately transmitter and receiver at a supersonic frequency. The receiver may then employ this interrupted oscillation for obtaining super-regenerative amplification. This principle is adopted in the system to be described.

The idea of using a super-regenerative receiver for *simultaneous* transmission and reception seems to have been put forward first in May, 1928, by G. A. Beauvais.[2] Later in the same year a patent was taken out by Lorenz A.G.,[3] and in 1931 a similar system was patented by the Marconi Company.[4] These early systems appear not to have been ideal. In the Lorenz system there seems to have been difficulty in maintaining synchronism between the quench oscillators at the two sets. From our experiments we expect the Marconi system

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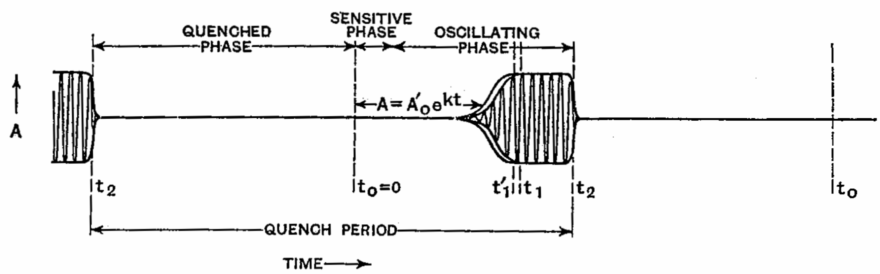
was found to be liable to distortion and background noise.

(b) The Modulated-Quench Duplex System
The apparatus consists essentially of a super-regenerative receiver employing a relatively powerful radio-frequency oscillator quenched at a supersonic frequency by a separate oscillator. The two sets in communication are exactly similar, and the quench frequencies are synchronised. With a suitable circuit it is found that the two quench frequencies lock to one another in a remarkably stable manner. For example, a signal produced by radiating a quenched oscillation of ⅛ watt average power on 3 metres wavelength from a λ/2 aerial is sufficiently strong when received on a λ/2 aerial at a distance of 25 miles, to lock the quench frequency of a similar oscillator with sufficient stability for practical purposes.

In one cycle of this quenching process three consecutive states may be recognised, which may conveniently be termed the "quenched," "negatively damped" (or sensitive), and "oscillating" phases. In the "quenched" phase the oscillation dies to zero or more strictly to a residual E.M.F. in the circuit which is only that due to thermal agitation, shot effect, etc., *and* the received signal. This quenched phase is followed by the relatively short "sensitive" phase, in which an oscillation builds up increasing exponentially with time, and the amplitude may therefore be written as A_0e^{kt}. A_0 therefore comprises the random agitation E.M.F. together with the E.M.F. produced by the received signal. When in course of time e^{kt} has reached the value 10 or 100, the received signal is such a small part of the oscillation that any modulation of the received signal would be practically without effect on the

Fig. 1. — Diagram to illustrate the theory of the Super-regenerative receiver.



increasing oscillation, so we may say that we have passed out of the sensitive phase into the oscillating phase. But it is important to note that the oscillation amplitude is still at any time proportional to A_0, the small received signal and agitation E.M.F. A limit is however reached when A_0e^{kt} is the maximum oscillation which the valve will maintain, A_{max} say. Clearly the greater A_0 the sooner this limit is reached and hence the oscillation persists at the maximum for a longer time, assuming that it is cut off at a definite phase of the quench cycle corresponding to the onset of the quenched phase. This is illustrated in Fig. 1. It should be noted that, if the function A_0e^{kt} is plotted against time for different values of A_0, all the curves appear of the same shape but displaced on the time scale. The same proportional change of A_0 produces the same displacement on the timescale whatever the absolute value of A_0.

When the relative phase of the two synchronised quench oscillations is suitably adjusted, telephonic communication may be established by a *very slight* modulation of the quench oscillator.

Before discussing the detailed working of this system, it seems advisable to review briefly the theory of the super-regenerative receiver, [5, 6, 7,] as no very satisfactory account appears to have been published yet in English.

The Theory of the Super-Regenerative Receiver

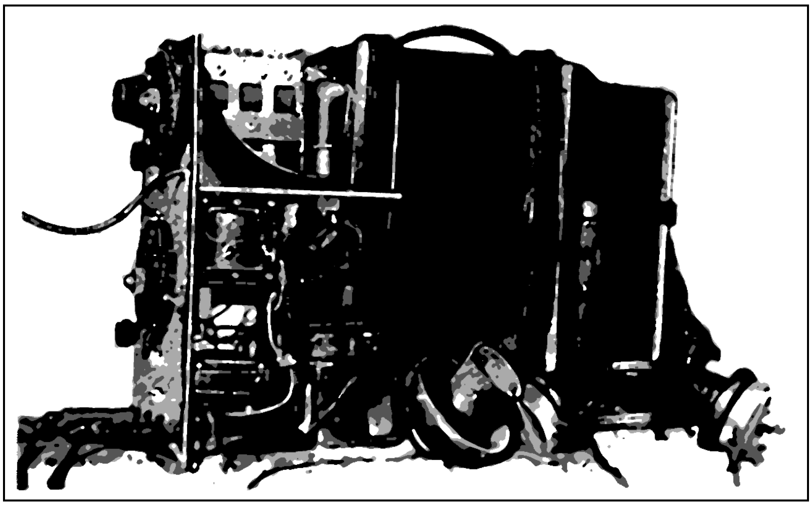
The super-regenerative receiver consists essentially of a radio-frequency oscillator, the oscillation of which is periodically interrupted or quenched at some high-audible or super-sonic frequency. The oscillation is then allowed to build up again, and it is in this building-up process that the amplification occurs.

Referring to Fig. 1, the increase of A_0 to A_0' (of the order of 10^{-6} cm. on the vertical scale of the diagram, and therefore quite invisible) due to change of amplitude of the signal reduces the time t_1, at which the oscillation reaches its maximum, to the time t_1'. Quantitatively, $t_1 = -\frac{1}{k}\log A_0$ + constant,

and $t_1' = -\frac{1}{k}\log A_0'$ + constant.

Therefore $t_1 - t_1' = \frac{1}{k}\log\frac{A_0'}{A_0}$.

Also the duration of the full oscillation may be written as $t_2 - t_1 = \frac{1}{k}\log A_0$ + constant. This expression contains the explanation of the remarkable automatic volume control action of the super-regenerative receiver.[5] For if the current in the anode circuit (*i.e.* through the phones) changes by δi in passing from the sensitive phase to the full oscillating condition, then the total current through the phones may be written as $\frac{n}{k}\log A_0.\delta i$ + constant, where n=quench frequency. The constant current component produces no sound in the phones, the other component is proportional to $\log A_0$. If the received signal is so large that the residual agitation E.M.F. is negligible in comparison, A_0 is proportional to the amplitude of the received signal. If this received signal is modulated we may have $A_0 = A_S(1 + m.\sin\omega t)$ and the current through the phones due to the signal is $\frac{n\delta i}{k}\log A_S.(1+m.\sin\omega t) = \frac{n\delta i}{k}\log A_S$ (which is a constant) $+ \frac{n\delta i}{k}\log(1 + m.\sin\omega t)$.



A close-up view of the complete set.

The component due to the modulation is seen to be $\frac{n\delta i}{k}\log(1 + m.\sin\omega t)$, which is independent of A_S, the absolute signal strength, but depends only on the depth of modulation m. Expressed another way, the loudness of the received modulation depends only on the depth of modulation and not at all on the amplitude of the received signal, and this is true provided that the amplitude of the received signal is considerably greater than the residual agitation E.M.F. in the receiving circuit. It may be noted that this perfect automatic volume control is necessarily accompanied by a slight distortion on normally modulated signals, for $\frac{n\delta i}{k}\log(1 + m.\sin\omega t)$ may be expanded as

$$\frac{n\delta i}{k}\left(m.\sin\omega t + \frac{m^2}{2}.\sin^2\omega t + \ldots + \ldots\right);$$

if m is not greater than ½ ($m \leq$ ½), then the distortion terms are $\leq \frac{m}{8}(1-\cos 2\omega t)$.

It is only on short wavelengths that the behaviour of a super-regenerative receiver is in accord with this theory. On longer wavelengths (above about 300 metres) the oscillation does not build up to the full value during the quench cycle, unless the quench frequency is in the audible range. If the oscillation does not build up fully, the automatic volume control action is impaired.

It is characteristic of the super-regenerative receiver that, in the absence of a signal, a rushing noise is heard in the phones. This is clearly due to the oscillation building up from the random disturbance in the circuit. Quite a weak signal of the correct frequency is however sufficient to swamp this disturbance and thus to quieten the background. It will be realised that this effect is due to the automatic volume control action. An exactly similar effect is commonly observed with modern broadcast receivers employing automatic volume control; in the absence of a signal the receiver is most sensitive and brings in background noises. Under some circumstances it might be desirable to apply a system of quiet automatic volume control to reduce the noise in the absence of a signal. Any rational attempt to reduce the background noise when receiving a signal must aim at reducing the random E.M.F. in the oscillatory circuit relatively to the received signal.

It is to be noted that no receiver can be more sensitive than a super-regenerative receiver unless the random disturbance in its first circuit is less than in that of the super-regenerative receiver.

Factors affecting the output of the super-regenerative receiver must be sharply distinguished from those affecting its sensitivity. The output power is proportional only to the change of power dissipated in the anode load between the oscillating and the sensitive conditions, and to the number of interruptions per second (the quench frequency). It is not yet clear how the effective random disturbance in the oscillatory circuit of a super-regenerative receiver depends on the maximum power which may be developed. But it appears that the disturbance does not increase very rapidly with the oscillator power: a powerful oscillator may still be a sensitive receiver. (This is required for satisfactory duplex working.)

From these considerations there is no reason why any audio-frequency amplifier should follow a super-regenerative receiver. It may however be more economical to use a low-power oscillator, followed by an audio-frequency amplifier, than to use a more powerful oscillator.

The amplification provided by a super-regenerative amplifier may be phenomenal, for example a quenched oscillator dissipating from 1 to 4 watts provides amplification of the order of 5.10^8 expressed as the ratio of the audio-frequency output power to the radio-frequency input power, for a wavelength of 3 metres. It should be noted that this amplification is obtained from a single triode valve.

Mode of Operation of the Modulated Quench Duplex System

It has already been mentioned that the quench oscillators of the two sets are adjusted to a common frequency. This frequency and the phase relation between the two quench cycles are so adjusted that the pulse transmitted by one set reaches the other in its sensitive phase, and that the oscillation pulse which then builds up in this receiver and is transmitted, reaches the first set in its sensitive phase.

It will be clear that the adjustment will depend on the distance between the two sets, owing to the time taken by the pulses in transmission over the distance. For example, the performance of two actual sets may be quoted. At distances up to 200 yards any quench frequency in the tuning range, 50 to 100 kc/s., might be used. At from 200 yards to ¼ mile, only the lower quench frequencies could be used. For distances of ¼ to ½ mile a high quench frequency is most suitable. For still greater distances the correct frequency must be found by trial. Having selected the quench frequency according to these rules, satisfactory duplex working may be achieved by adjusting quench oscillator anode supply, and by a fine adjustment made at one set only of the quench oscillator tuning, keeping within the range over which the quench frequencies remain locked.

When the theory of operation is considered more exactly, it will be realised that it is necessary for a modulated part of the pulse from each set to reach the other in its sensitive phase. Now by the method of modulating the quenching oscillation, the maximum amplitude is only very slightly changed, but the duration of each pulse is changed, *i.e.* the ends of the pulses are modulated. For, as was pointed out earlier, a displacement of the instant at which the oscillation starts to build up is equivalent to a change of the initial amplitude of the oscillation. The same is true of the ends of the pulses: when the set passes from the oscillating to the quenched phase, the amplitude of the oscillation decays exponentially (and very rapidly). A displacement on the time scale is therefore again equivalent to a fractional change of amplitude proportional to the time displacement.

evident that the instant R can only be made to coincide with a part of the dotted curve having a steep slope by suitably choosing the quench frequency with regard to the separation or propagation time-interval between the two sets. Duplex working is therefore only possible with certain quench frequencies, which, when set A is being locked to set B, allow the sensitive instants of set B to occur either at the beginning or end of the pulses received from set A.

The duration of the pulses radiated is controlled not only by modulation of the quench oscillator, but also by the received signal. This also follows from the equivalence of a change of initial amplitude and a time displacement of the sensitive instant. The resulting modulation appears to be quite large, and we have found that it may be used to provide a relay action between two sets out of range of one another. When a third set is placed halfway between them, and can "communicate" with each of the others separately, and the quench frequencies of all three are locked together, the three sets can all "hear" one another. Similar "conference" operation is also usually possible when all three sets are able to work to each other in pairs, but the necessary adjustment is difficult and impracticable for mobile sets.

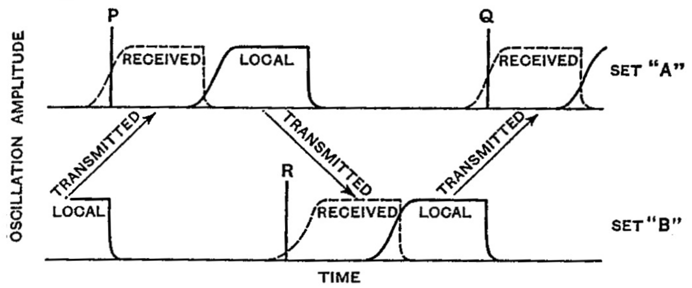


Fig. 2. — Diagrams indicating performance of the two sets.

The diagrams of Fig. 2 show the sequence of events at the two sets, A and B. (It should be noted that the dotted curves of the amplitude of the received signal are *greatly magnified*, until they appear to be of the same order as those of the local oscillation.) Since modulation is effected by displacing the ends of the pulses, the condition for sensitive reception is that the received amplitude should be changing rapidly with time at the sensitive instant of the receiver. This is indicated in the diagrams, where P and Q are sensitive instants of the set A, and R such an instant for the set B.

A partial explanation of the mechanism of locking of the quench oscillators appears from this figure. As drawn, it shows the set A receiving the beginnings of the pulses from set B. Should the interval PQ be longer than the interval between the received pulses (*i.e.* the quench frequency of set A be lower than that of set B), then the amplitude at time Q, from which the local oscillation starts to build up, is increased: and we have seen that this is equivalent to its having started at an earlier time. The next pulse of set A is therefore speeded up, and synchronism tends to be established.

The "local oscillation" of each set is radiated, and becomes the "received signal" at the other: each dotted curve is therefore a replica of the solid curve of the other diagram, but occurs later by the time taken in transmission. It is

Modulation of the radiated pulses by the received signal is quite efficient compared with that produced by modulating the local quench oscillator. One incidental result of this is that the "side-tone" at the transmitter is perceptibly increased by the re-radiated pulses from the distant station.

Normally the sets are remarkably free from “side-tone," that is to say the speaker scarcely hears his own voice in his receiver. This fact makes it possible to connect the sets to ordinary telephone lines without any trouble from acoustic instability. Alternatively it is possible to use a loud speaker instead of phones for reception without incurring microphone howl.

The Circuit

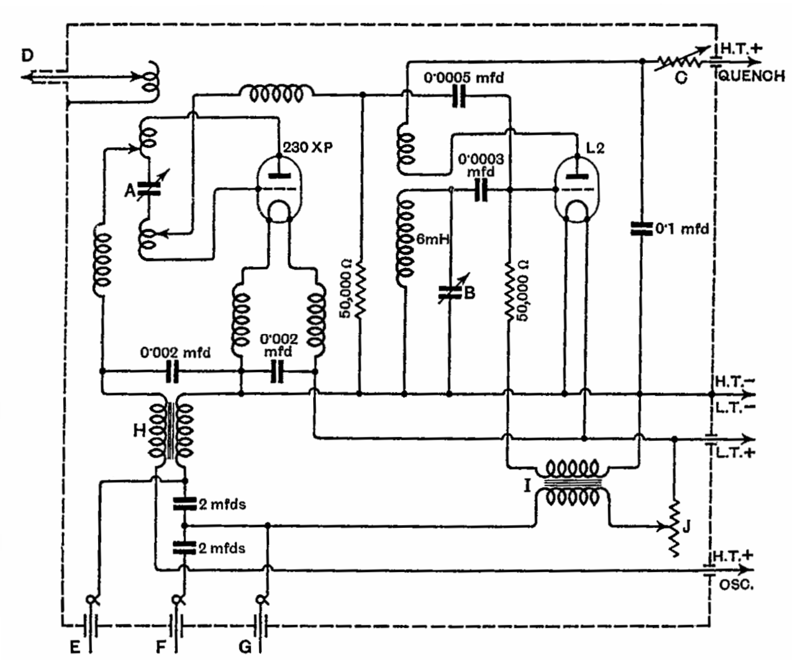
The circuit of the most successful apparatus used is shown in Fig. 3. The essentials are:

(1) An ultra-short-wave oscillator quenched at a supersonic frequency. This in addition to providing the transmitted oscillation also acts as a super-regenerative receiver. It therefore has a telephone transformer in the anode circuit and, also, in order to obtain a reasonably loud audio-frequency output, the grid circuit includes a resistance of about 50,000 ohms. The automatic volume control action characteristic of this type of receiver makes any additional volume control practically unnecessary.

(2) A speech-modulated supersonic quench oscillator. If the quench oscillation is fed to the grid circuit of the radio-frequency oscillator, the quench oscillator may be of lower power. Further, since only a slight degree of modulation is required, this may be supplied by a microphone and transformer in its grid circuit. The amplitude of the quench oscillation must be adjustable. This is conveniently done by adjusting a variable resistance in the H.T. lead. The frequency of the quench oscillator must also be adjustable over at least one octave, if communication is to be obtained at all distances.

It is *essential* that the coupling between the quench oscillator and the radio-frequency oscillator be such that harmonics of the quench frequency may be passed back efficiently from the radio-frequency oscillator to the quench oscillator. If this condition is not satisfied it is in practice impossible to lock the quench frequencies with a constant phase difference. Quench oscillators of the multivibrator type have been tried. These locked more readily, as would be expected, but it was found that they were also less stable against other disturbances, and modulation was not so satisfactory.

In other respects the circuit given may be modified as may be convenient. One or two points may however be mentioned. The radio-frequency oscillator should be as efficient as possible. With ordinary valves the circuit given seems very efficient. In this the filament current is led through a radio-frequency choke in which the two wires are wound parallel on the same core and the wires are bridged by a condenser at the end farthest from the valve. The anode and grid circuit leads are fine wires suitably coiled and coupled to the oscillatory circuit to obtain maximum output. The set is mounted in a screened box to avoid hand-capacity effects, which are other-wise troublesome, especially on the quench tuning. It is very convenient to feed the λ/2 aerial at



Fig, 3. — Circuit diagram of the duplex radio-telephone finally adopted by the authors as the most successful tried. The components of the circuit are as follows :—

A, Radio-frequency tuning 0.0001 μF; B, Quench-frequency tuning 0.0015 μF; C, Quench Amplitude control 50,0000 Ω; D, Concentric feeder to λ/2 antenna; E, Ordinary Line connection or L.R. Phones; F, Line connection with series condenser or L.R. Phones; G, Microphone or Combination Hand-set; H, Telephone Transformer ratio 10:1 ; I, Microphone - Transformer ratio 30:1; J, Microphone Sensitivity Control.

its mid-point from an untuned concentric type feeder. The outer conductor of this feeder is "earthed" to the screening box, and the feeder is coupled to the oscillatory circuit by a few turns of thick wire adjusted by trial. When connecting the microphone and telephone transformers to a common line, the correct interconnection should be adopted in order to ensure absolute stability. It is also advisable to include a variable resistance in series with the microphone so that the sensitivity may be increased when the set is worked from a long line. The radio-frequency oscillator valve should have a low impedance so that the necessary grid resistance does not cause it to "squegg."

There is another important consideration affecting the choice of this valve. It is found that in general the radiated frequency is slightly higher than the frequency to which the set is most sensitive as a receiver. This seems to be due to a change in the effective inter-electrode capacities of the valve between the oscillating and the sensitive conditions, and depends on the type of valve used. In this respect the Cossor 230 XP has been found the most satisfactory of the small-power valves that we have tried. This valve is also convenient as the leads to the electrodes are short and reasonably thick, so that the external circuit for a wavelength of 3 metres is not inconveniently small.

It will be clear that the reason for adopting the ultra-short waves is that this system occupies a wide frequency band. It is, however, to be noted that as the overall modulation is very slight, the audio-frequency interference is small as long as the quench frequency of the receiver is not locked to that of the interfering transmitter.

The H.T. power supply to our sets is about 20 mA. at 150 volts (3 watts). The aerial current at the centre of the $\lambda/2$ aerial is then about 40 mA. as indicated by a Weston type 425 thermo-milliammeter.

The total weight, including the batteries, need not exceed about 20 lbs.

Performance

The performance of the actual sets may be summarised as follows. Duplex telephony with first-class quality and silent background is obtainable with quite simple tuning adjustments up to a distance of about ¼ mile over reasonably open flat ground. Up to this distance a quench frequency of 50 to 60 kc/s. may be used, and communication may be maintained with one set on a moving car without any necessity for altering the adjustment.

At greater distances the quench tuning adjustment depends on the distance between the sets; and as the signal strength falls off quality becomes marred by increasing background hiss. This is, however, no worse than is observed with an ordinarily modulated transmitter of the same power. At the extreme limit of range, where it might be just possible to catch familiar phrases using a straight transmitter, it is found with the modulated quench system that the quench locking becomes difficult to maintain.

The range obtainable with these sets depends very markedly on the sites chosen. With aerials not reaching more than 6 feet high, the effective range over flat ground is found to be about ⅝ mile. With favourable sites at the top of steep slopes, however, a greater signal strength has been obtained over 25 miles, and reasonably satisfactory duplex telephony has been carried out at this range.

The disparity between these figures is an instance of the surprising characteristics of the propagation of waves of these wavelengths. The main features of the difference from longer wavelengths are explained on the generally accepted hypothesis,[8 9 10] that (1) these waves are too short to be reflected at all from the Heaviside layer, (2) strong reflection, with reversal of phase, takes place from the surface of the ground. The earth behaves as a dielectric at these frequencies, and (for 3-metre waves at approximately grazing incidence) as practically smooth. If the transmitter and receiver are situated at ground level, therefore, the direct ray and the ray reflected at the ground are received almost exactly out of phase and with equal intensity. There is thus a minimum of signal strength along the surface of the ground. As the sets are raised above the ground, a path difference is introduced between the direct and the reflected rays, and the signal strength is increased. (The strength at a fixed height is proportional to the inverse *square* of the distance, and not to the inverse of the distance, since the path difference is smaller the greater the distance between the sets.)

The best site for an aerial is therefore at the edge of a precipice facing the distant station, or at the top of a high mast or building: not only (as is still commonly supposed) because a more distant horizon is obtained from a height, but also because a path difference is introduced between the direct ray and the ray reflected from the surface of the ground.

It was stated by Beauvais in 1930[11] that it was most unfavourable for transmission if the waves left the transmitter or arrived at the receiver at grazing incidence over the surface of the ground for even a short distance, while the path of the waves might pass for miles over the surface of the earth or sea, midway between the transmitter and receiver, without much attenuation. The waves are, however, rapidly attenuated below the horizon. These conclusions have been substantiated by all subsequent workers. We may quote briefly the results of one or two of our experiments bearing on these points. (It must be emphasised that the super-regenerative receiver is so sensitive that these propagation phenomena are in evidence even with the low power radiated by our sets.)

While signals cannot be received beyond a range of about a mile over flat ground, we have received signals at a distance of 47 miles with the sets at the top of steep hills rising 500 ft. from flat country, one near Folkestone and the other near Eastbourne. In this case intervening hills rose 300 ft. above the line of sight (allowing for atmospheric refraction) for a distance of 2 miles. However, the atmospheric refraction may have been abnormally strong during this test. It is much more certain that diffraction was important when a similar test was made on the Yorkshire moors. Fairly strong signals were received when the transmitter and receiver were well situated at the top of steep hills about 7 miles apart. An intervening table-land rose more than 200 ft. above the line of sight for 3 miles. Signals could *not* be received at the centre of the table-land: it seems certain that this was due to the destructive interference caused by the ray reflected there from the ground.

Trees, buildings, and other objects of dimensions comparable with a wavelength produce very marked standing wave patterns. When an aerial is set up inside a building, it is almost essential to move it to a suitable position which in practice can only be determined by trial. The proximity of trees or buildings is, however, much less detrimental than that of open flat ground.

Conclusion

We have been mainly concerned with the practical aspects of communication on ultra-short-waves with portable sets. Nevertheless, it is hoped that this account may be of interest to those concerned with other aspects, for example the synchronisation of frequencies by radio, and the attainment of true duplex radio-telephony. It may be that the simplicity of the system for working over a fixed range is of more account than its portability. In common with other portable ultra-short-wave apparatus, it is at its best when used for temporary communication in mountainous districts. It seems probable that it will be many years before mutual interference on ultra-short-waves becomes a practical problem in the remoter districts.

References

1 L. S. Palmer, *Wireless Principles and Practice,* p. 410, Longmans, 1928.
2 G. A. Beauvais, *L'Onde Elec.,* Vol. 7, p. 206 (1928).
3 Lorenz, Brit. Pat. No. 312,079 (1928).
4 Marconi, Brit. Pat. No. 388,213 (see also No. 389,225) (1931).
5 H. O. Roosenstein, *Hochf:tech. u. Elec:akus.,* Sept. 1933.
6 H. Barkhausen and G. Hässler, *ibid.* Aug. 1933.
7 G. Hässler, *ibid.* Sept. 1934, Vol. 44, p. 80.
8 Trevor and Carter, *Proc. Inst. Rad. Eng.*, Vol. 21, p. 387 (1933).
9 Schelleng, Burrows, and Ferrel, *ibid.* p. 427.
10 Englund, Crawford, and Mumford, *ibid.* p. 464.
11 G. A. Beauvais, *Annales de P.T.T.,* April 1930.