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*Techniques for the Application of Ionosphere Data to Practical Short Wave Transmission and Reception**

By T. W. BENNINGTON

RADIO communication over long distances across a spherically shaped earth is only possible because there exists a medium which is capable of diverting the waves from the straight paths they would otherwise travel, and of so shaping these paths that the earth's surface can be followed. That medium is the atmospheric region we call the ionosphere. Every time we send out a radio signal, we make use of the ionosphere for the propagation of our signal. So it is important for us to know something about this region, and about how it is likely to deal with our signal during its passage across the world. Having evolved highly complicated and efficient receivers and transmitters, with their equally elaborate and efficient aerial systems, we would be extremely unwise to neglect one of the most vital and important links in the chain of communication, and so deny ourselves the full reward for our technical achievements.

Since the classical experiment in ionospheric measurement made by Sir Edward Appleton in 1925, both the techniques and the facilities for making such measurements have been constantly improved and expanded. There now exists, in positions widely distributed over the earth's surface, a network of ionosphere measuring and recording stations, constantly engaged upon the work of ionosphere examination, so that adequate data shall be available for the benefit, not only of the scientific investigator, but also of the short-wave engineer and—perhaps incidentally—the amateur radio man. It is about the work of these stations, and about the technique for applying the accumulated data obtained by their efforts, that this paper mainly deals.

Historical

The need for the existence of some sort of conducting region in the high atmosphere was first felt in 1902, when Marconi succeeded in picking up signals in Newfoundland from his station at Poldhu in Cornwall. Transmission of signals thus far over the earth's surface required some explanation, because it was known from Clerk Maxwell's theories, and from the experimental work of Hertz, that radio waves normally travel in perfectly straight lines—that is, provided that they travel all the time in a medium which has constant electrical properties. Since they had proved capable of bending themselves around the earth's surface, and since the bending process could not be explained in any other way, it became evident that they had been guided along in a manner similar to that which Hertz had shown possible by means of a metal sheet. So Oliver Heaviside and Dr. A. E. Kennedy came forward with the theory that the air in the upper atmosphere was not an insulator, but a partial conductor, with electrons capable of considerable movement. And so it eventually proved to be, although it was some years before the experimental proof was fully established. That was in 1925, when Sir Edward Appleton succeeded in establishing the exact location of the Kenelly-Heaviside layer by radar methods.

He discovered that the actual structure of the ionospheric region was not so simple as Kenelley and Heaviside had supposed. There were, in fact, not one, but several layers, lying one above the other in the atmosphere. Furthermore, it was found that not only the ionisation, but also the actual height of these layers varied constantly and considerably, from night to day, from summer to winter, and also over the 11-year sunspot cycle.

Critical Frequency

The reflecting power of any layer depends firstly upon the ionisation prevailing within it, secondly upon the frequency of the radio wave, and thirdly upon the angle of incidence which the wave makes with it. For a given degree of ionisation, the reflecting

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* *An abridged version of a paper read to the Society at a meeting held on May 30, 1947, at the Institution of Electrical Engineers, London.*

power is proportional to the square of the wavelength, or inversely proportional to the square of the frequency. If a wave is sent vertically upwards, and the frequency is gradually increased, a frequency is reached at which the layer is no longer capable of returning the wave to earth. This frequency is called the "Critical Frequency." As the ionisation in the higher or "F" layer is always—at least under normal conditions—greater than that in the lower, or "E" layer, the critical frequency of the former is higher than that of the latter.

If the wave is sent up obliquely instead of vertically, then higher frequencies are returned than is the case for the vertically travelling wave. For every angle of incidence on the layer—corresponding to every distance it is required to cover—there is a high limiting frequency. When the obliquity of the wave-path is such that it is leaving tangental to the earth's surface, covering the maximum possible distance, then the highest possible limiting frequency is reached, and transmissions over any further distance can be accomplished only by making more than one hop.

Ionosphere measurements are most conveniently made by sending pulses of energy vertically upwards, so as to observe the height from which they are returned on any particular frequency. Then, as the frequency of the measuring equipment is gradually increased, the critical frequencies of the lower layers are observed and recorded. It is a fascinating sight to see these measuring operations being performed at a station such as the one operated at Datchet by the Radio Research Board, and to watch, upon the screen of a cathode ray tube, the echo returning, as it were, from the sky. The height to which the pulse has travelled is determined, of course, by its distance to the right along the trace of the cathode ray tube, for that is a measure of the time it has taken on its journey. At first there appears the single and well-defined echo, being returned from the "E" layer—that is, of course, in addition to the ground pulse. As the frequency of the transmitter is automatically increased, there suddenly appears, at a point much further along the trace, another well-defined echo, indicating the first return of energy from a layer much higher in the atmosphere, in fact from the "F" layer. Then the first echo pulse gradually moves along the trace, decreases in size, and finally disappears, showing that a frequency has been reached at which no more energy is being returned from the "E" layer. The other pulse, meanwhile, moves slowly to the right, indicating that the height from which it is being returned is gradually increasing. Next, an interesting phenomenon occurs; the pulse becomes split in the centre, and two separate, well-defined pulses appear. This is in exact accordance with the magneto-ionic theory of a wave traversing an ionospheric region permeated by a magnetic field—the earth's field, of course—and is caused by the wave being split into two components, the so-called "Ordinary" and the "Extraordinary" wave. Finally, with the frequency continuing to increase, the two pulses move faster and faster to the right, indicating deeper penetration by the waves into the medium, until first one and then the other diminishes and vanishes entirely—the energy at this frequency penetrating into outer space.

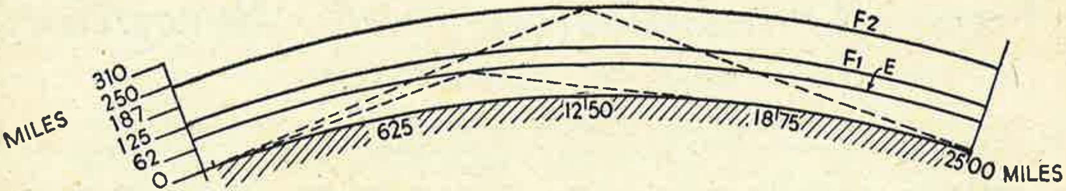


Fig. 1.
General structure of the Ionosphere, summer day-time condition. Dashed lines indicate two possible paths for radio waves and show the maximum distances for a single hop.

The Solar Cycle

The ionosphere variations conform, in general, to the 11-year cycle of sunspot activity. These cycles, however, do not follow each other with a precise degree of regularity, either in time or in magnitude. As a matter of fact they differ considerably in both, and here arises the necessity for the accurate prediction of the variations for some time ahead, which is one of the main purposes of all this accumulation of data. Although this prediction work is by no means a simple operation, nor yet one which is likely to yield precisely accurate results, still, a study of the solar cycle trends and their accompanying ionospheric variations during the past few years does yield information that we can apply with some measure of success to our future planning operations.

MUF's and OWF's

The effects of the solar cycle are, of course, that, at the sunspot minimum, the critical frequencies, and hence the maximum usable frequencies (MUF's), are relatively low, both by day and night, the world over. At the sunspot maximum, they are relatively high. The problem in forecasting is mainly to predict exactly how the solar activity will vary, and to what degree the critical frequency will respond, at every hour of the day, during every month of the year, at every point on the world's surface. An indication of the nature and extent of these changes in the characteristics of the ionosphere will be obtained by studying Figs. 2, 3, 4 and 5, bearing in mind that all the variations are occurring simultaneously. It is important also to note that these are the MUF's for various distances, etc., obtained from the measured critical frequencies *averaged* for one particular month. Hence they show the frequencies up to which the ionosphere will sustain propagation, *providing average conditions prevail.* But, as shown in Fig. 5, there are considerable variations from day to day; the ionisation—and the critical frequencies with it—varies up and down about the average from day to day. On certain days, when it is well below the average for the month, we should be in a dangerous position if we worked on frequencies right up to this MUF. The remedy, therefore, is to work on frequencies somewhat below the average MUF for the distances over which we are communicating, in order to ensure that, on days when the ionisation is below average, we are not working above the MUF. This lower frequency is known as the "Optimum Working Frequency," or OWF.

That, then, is the way the engineer has to arrange things, in order to be sure that his service is continuously maintained. But the radio amateur's requirements are different—namely, to get the best out of a particular frequency band, and to establish contacts whenever the ionosphere happens to be capable of dealing with his signal. He is not interested in these safety margins, or, if it comes to that, in the

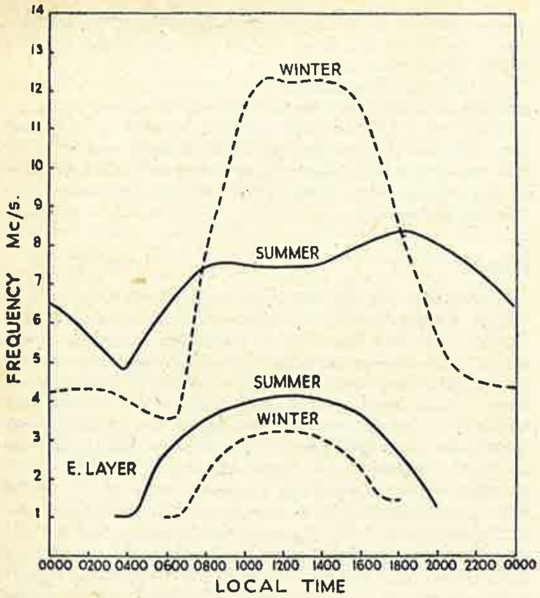


Fig. 2.
Diurnal variation in critical frequency—F2 layer. Washington, D.C. Lat. 40° N.

average MUF, but is quite prepared to work well above the average MUF on the mere chance of his signal getting through. An analysis of the measurements during one particular month, shown in Fig. 5, gives an indication of the nature of the difference between the requirements of the engineer and the amateur, and shows what high MUF's might be used if one desired to use only the very highest frequencies. It is interesting to note that the MUF during the worst storm day of that month was very much below that prevailing on most days of the month, and even below the OWF. The subject of ionospheric storms is dealt with later on.

" E " Layer in Control

When we transmit over medium distances, say up to 1,200 miles, the waves may travel to their destination by way of the " E " layer rather than the " F " layer. This distance would include most of the continent of Europe. Because the " E " layer is much lower in the atmosphere than is the " F," it is, with a given value of ionisation prevailing, able to sustain propagation on higher frequencies over these medium distances than is the " F," even though the latter has a higher degree of ionisation. This is because the angle of incidence on the " E " layer is much greater than that on the " F," so that, during a summer day, when the " E " layer ionisation is at a particularly high level, that layer often—for these medium distances—sets the high limit to the MUF. That is to say, the " E " layer, no matter what we do, controls the transmission, because any ray of radio energy which travels at the necessary angle to cover the distance, will, if it is able to penetrate the " E " layer, penetrate the " F " layer as well. In order to arrive at the MUF for these distances, we

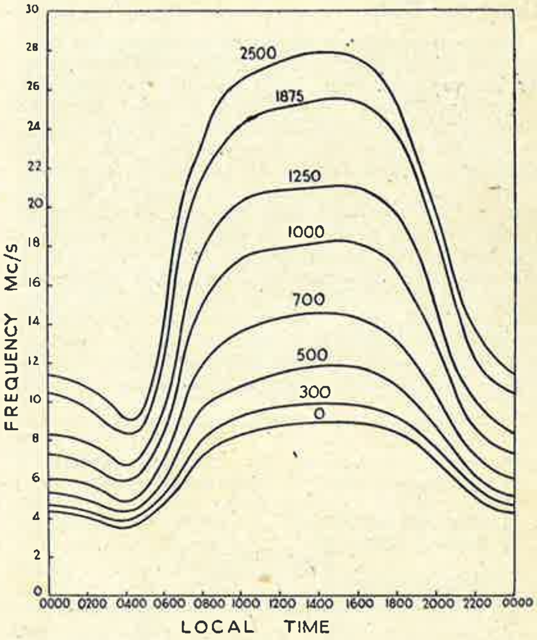


Fig. 4.
Predicted MUF (Maximum Usable Frequency) for use in I (Intermediate) zone—March, 1946. Lat. 50° N. Distances in miles.

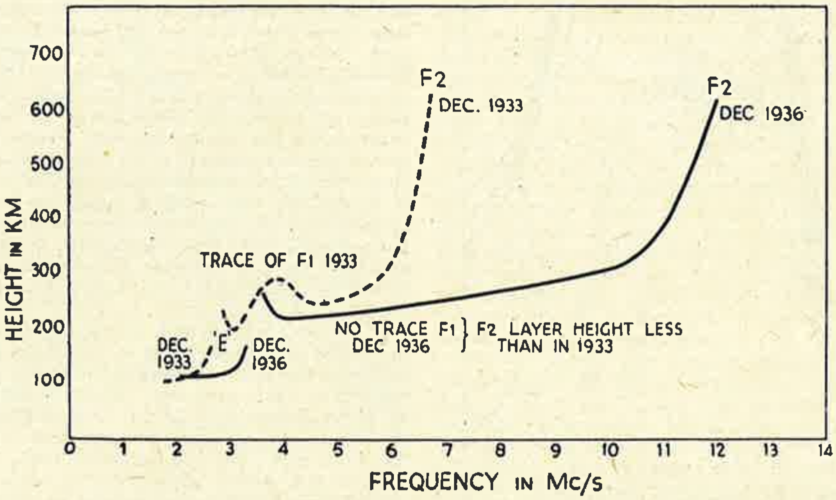


Fig. 3.
The increase of critical frequency with change from sunspot minimum (1933) towards sunspot maximum conditions.
Washington, D.C. Winter.

have to take into consideration the critical frequencies of both layers, a simple calculation enabling us to say which layer is controlling.

"Short Skip" or "Sporadic E"

The phenomenon known among amateurs as "Short Skip," or propagation by "Sporadic E" is caused by highly ionised "clouds" within the normal "E" layer. These sometimes have a critical frequency of up to 20 Mc/s., and can give rise to some really phenomenal results in short-wave transmission over medium distances. A "Sporadic E" critical frequency of 15 Mc/s. means an MUF (for 2,300 kilometres) of 78 Mc/s., and this explains some of the peculiar results which have been noticed.

Using the Data

The method usually employed to portray the data depends on the fact that, since the world turns upon its geographical axis, it is possible to transpose longitude for time. If, therefore, we take a Mercator map, and along its horizontal axis, mark the twenty-four hours of the day, then we may plot, in the appropriate position and under the correct local time, a whole day's measurements as obtained at each station. By drawing lines through all the equal values, we have a plot of the world critical frequency contours on one particular day, if we assume that the same values of critical frequency occur in different geographical latitudes when they have the same values of local time. For example, on the parallel of 50° North, we assume that the same diurnal variations will repeat themselves at different times—quite a logical assumption to make, it would seem, since the sun's zenithal angle in any one latitude will have the same value at the same value of local time, as the world turns upon its axis.

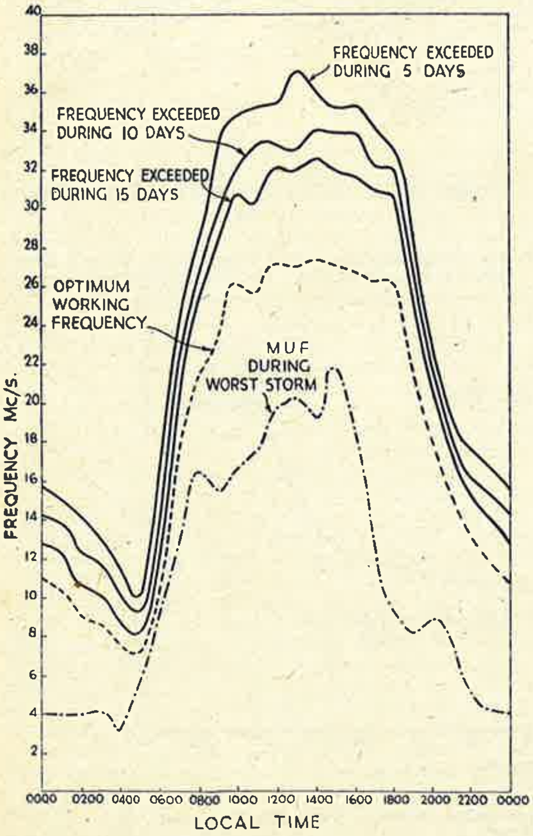


Fig. 5.
Maximum Usable Frequencies during March, 1946. 4,000 Kilometres.

If, instead of plotting the actual values obtained from the ionosphere research stations, we use them to predict what the average critical frequency value at that station will be during some future month, and plot these upon the chart, then the chart will be a plot of the average predicted world critical frequency for this future month.

Zones

Unfortunately for us, there is a further difficulty, which increases the complexity of the matter still further. It has been found that the assumption we made, that the same value of critical frequency would apply all along any parallel of latitude at the same local time, is an incorrect one. In fact, the critical frequency varies not only according to the geographical longitude and latitude, but also according to the *magnetic* latitude and longitude as well. The complexity arises because the magnetic axis of the world has no relation to local time, and the solution is to make a sort of compromise between the geographical and the magnetic influences on the critical frequencies. We divide the world into separate zones, and plot separate charts for each zone. The boundaries of the zones are certain magnetic meridians, and all the ionospheric measurements obtained from stations lying within a particular zone are used in the construction of the chart for that zone. The chart will then not be quite correct for the whole of the zone, since the magnetic influence will tend to vary across it, but it will show the average conditions prevailing in that zone.

MUF Contour Map

This, then, gives us a reasonable approximation of the critical frequency likely to prevail within any particular zone. However, a complete picture of the predicted critical frequency is not necessarily what we want. Therefore, we find it more convenient to calculate from the critical frequency contours, the corresponding MUF's for the maximum possible distance coverable, namely, 4,000 kilometres. We then, as a final effort, plot a chart for each zone, showing the predicted MUF for 4,000 kilometres.

These charts are drawn up on transparent paper, so that they can be placed over a Mercator projection map, upon which is drawn any particular transmission path. Then, by observing the transmission path beneath the MUF contours, we can see the conditions prevailing along the whole of the path, and, furthermore, by sliding the chart along, to represent the rotation of the earth, we can observe conditions prevailing over the path at all times of the day, in any convenient time standard, such as G.M.T. In Fig. 7 is shown one such contour map, for March, 1946, placed over the Mercator map, with transmission path shown. The time represented is 04.00 G.M.T., as shown by the fact that the Greenwich meridian on the map coincides with 04.00 hours on the transparent contour-map.

If our transmission path is exactly 4,000 kilometres in length, all we need do is mark off the point at the centre of the path, this being the point at which the wave is in the ionosphere. Then, by reading off the MUF for all hours of the day at that point, in terms of G.M.T., we can construct a predicted MUF curve for that particular transmission path. Later, by deducting a certain percentage in order to allow a safety margin, we arrive at the optimum working frequency (OWF), and below that we can fit our allocated frequencies, and so obtain a schedule of working frequencies for the month in question.

Multiple Hop Transmissions

If the transmission path is greater than 4,000 kilometres in length, then transmission will be by multiple hops. Multiple hop transmission cannot be treated as a simple extension of single hop transmission theory, because, after the first hop, the mode of transmission becomes so complex that it is not practicable to divide the transmission path into a number of different hops and examine the ionosphere at the centre of each. There is considerable scattering of the energy each time it meets the ionosphere and earth, and there is the problem of lateral deviation by gradients in the ionisation, or by particular clouds in the ionisation. All this results in transmission over a multiplicity of paths, so that when it comes to the practical application of the ionosphere data to a multiple hop transmission path, a simple division into separate hops is impossible. Fortunately, however, a method has been found—more by experience than by anything else—which seems to fit the conditions very well. For all multiple hop transmission paths, it has been found that it is only necessary to consider the ionosphere at two points, each half the length of a hop of maximum possible length from the ends of the transmission path. We mark points on our Great Circle path, 2,000 kilometres from each end, and examine the MUF at those two " control points " by sliding the transparent contour chart over the map and reading off the MUF at whichever control point it has the lowest value. This will take account of the geographical variation in MUF along the transmission path. Should the two control points lie in different zones, then we read the MUF for each control point on different charts. This involves two operations with the transparencies, but, having read these values off, we then strike out the higher of the two, and we are left with the MUF for the path. We then construct a curve, showing the MUF and OWF for the whole path over the 24 hours for the month we are considering, and fit in our allocated frequencies in the way described for a single hop transmission.

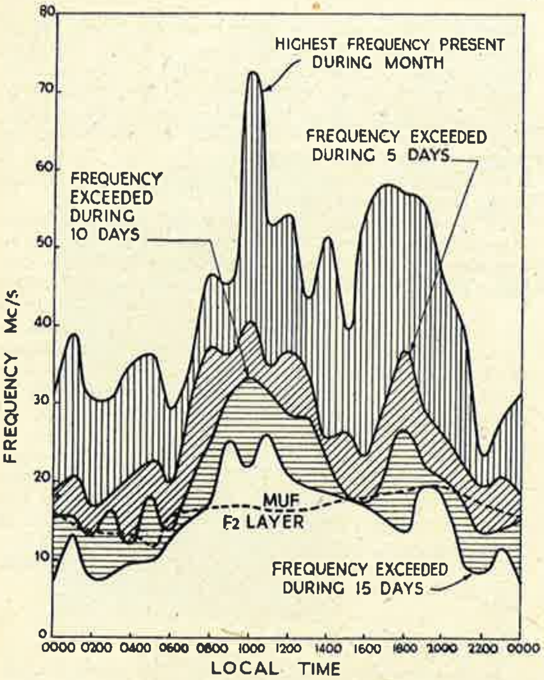


Fig. 6.

Sporadic " E " MUF—June, 1946. Slough, Bucks. 2,300 kilometres

There is also a lower limit—the " Lowest Useful High Frequency " or " LUHF," which is not controlled by the ionosphere alone, but depends on the ionospheric absorption, the atmospheric noise level, the power radiated and the required field intensity at the receiving end. It can be arrived at by the use of world contour charts of absorption and of atmospheric noise, but, for most purposes, the high limit by itself is sufficient. Radio amateurs are more likely to work above the MUF than below the LUHF.

In order to plan our schedule for a particular path, we should draw horizontal lines across the curve, corresponding to our allocated frequencies, fitting these to the curve so that the times to change to a higher or lower frequency are clearly indicated.

Present Trends

At the present time, we are approaching a sunspot maximum, and, though it is impossible to say with any certainty, we might hazard a guess that the maximum itself will occur this year (1947). The critical frequencies and MUF's all the world over have been increasing very rapidly indeed, ever since the sunspot minimum in 1944. With our improved and more widely extended ionosphere measuring arrangements, we have been able to follow this rapid increase much more closely than was the case during the last cycle, and a very interesting point emerges. Previously, the frequencies actually made use of for long distance transmissions did not exceed about 21 Mc/s. in the case of commercial and broadcast services, although amateurs did use the 28 Mc/s. band. At the last sunspot maximum, even the 21 Mc/s. band was thought by some to be rather high in frequency for broadcast transmission. Our experience during this cycle, however, shows that at the sunspot maximum, very much higher frequencies than any of these could be used successfully for regular long distance transmission. For example, on a transmission running in southerly directions from this country, the *average* MUF commonly exceeds 40 Mc/s., and the OWF about 35 Mc/s. It appears, therefore, that at the last sunspot maximum, we did not make use of such high frequencies as we might have done; and we should always remember that ionospheric absorption, of course, becomes greater with decreasing frequency.

Still, there are often obstacles—other than technical ones—to the use of the most efficient high frequency; to give just one, it is not much good broadcasting on a frequency which is not covered by the wave range of a majority of the broadcast receivers. It is interesting to note, however, that these high calculated MUF's have been well borne out by actual results. The reception of the B.B.C.'s transmission on 26 Mc/s. is consistently good in the parts of the world to which it is directed. Amateurs obtain, more or less regularly, during certain months of the year, very good results in the 28 Mc/s. band. The reception of British transmissions round about 40 Mc/s. has frequently been reported in many parts of the world, whilst reception in this country of U.S. Police and FM transmissions is a frequent occurrence during the equinoctial and winter months.

Finally, there is the notable case of the reception by amateurs in this country of a United States station on 50 Mc/s., and the reception of a Dutch amateur station on 50 Mc/s. in South Africa. This does not mean to say that 50 Mc/s. will ever become a regularly usable communication frequency, but it is probable that these particular transmissions went by the regular "F" layer of the ionosphere, and they are certainly interesting examples of how high the MUF for that layer can occasionally rise. The coming autumn should be even more propitious for the establishment of contacts on this frequency—although even then, we should not expect them to become everyday occurrences.

(*The author's prediction has been proved correct—numerous transatlantic contacts having recently taken place on frequencies between* 50 *and* 54 *Mc/s.*—ED.)

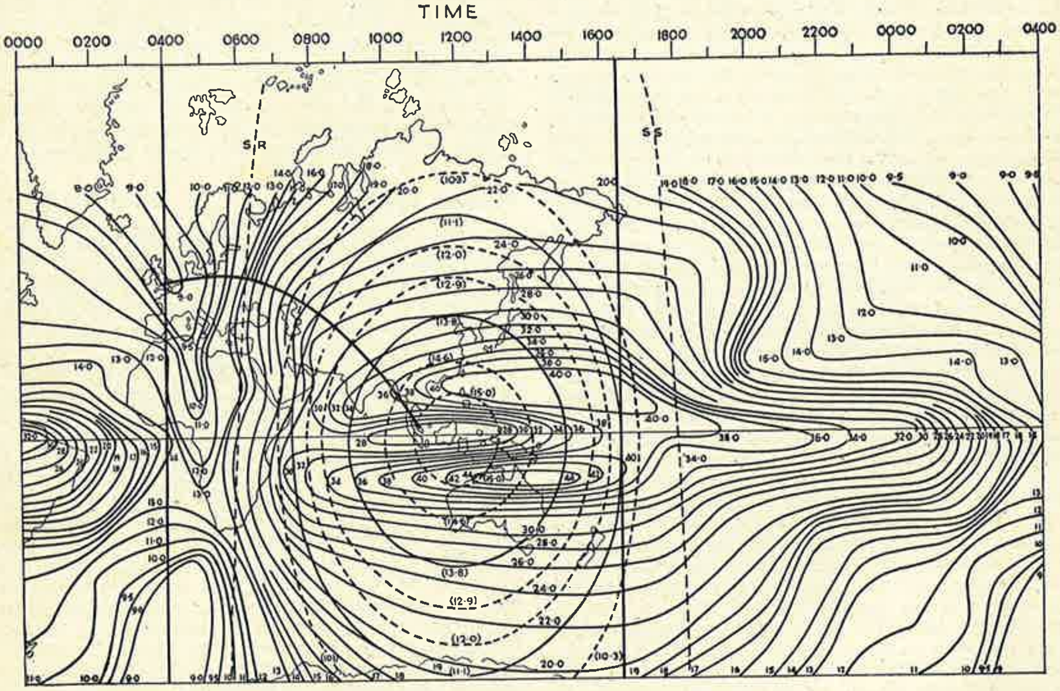


Fig. 7.
Maximum Usable Frequencies, I Zone, March, 1946.
E Layer ... 1,600 kilometres. F2 Layer ... 4,000 kilometres.

Ionosphere Disturbances

The ionosphere, although it has often been compared to a reflecting mirror held high in the sky, does not at all times retain unimpaired its mirror-like properties. At times, it becomes like an extremely tarnished piece of metal, having hardly any reflecting properties at all, at least to certain radio frequencies. In other words, it is subject to storms and disturbances, and these fall into two distinct kinds.

The "Dellinger Fadeout"

The first class of disturbance is known as the "sudden ionosphere disturbance," or "Dellinger Fadeout." It almost always occurs in connection with a solar flare on some part of the sun's visible disc. It appears that, from the flare, there is a burst of ultra-violet radiation, which, travelling with the speed of light, penetrates the atmosphere as far as the "D" layer—just below the "E" layer—setting up a body of ionisation, in which the sky waves from radio transmitters are completely absorbed. Short wave communication across the day-light zone of the world is, therefore, interrupted, either completely or partially, according to the intensity of the disturbance. Because the fadeout of radio signals is due to the *absorptive* effect of the ionised region, the lower frequencies are most affected, and the higher frequencies often escape interruption. When the fadeout ceases, as it usually does within an hour, the frequencies return into use from the high frequency end downwards.

These solar flares are random occurrences, and, therefore, there seems to be no possibility of making a prognostic of their outbreak, and, therefore, none of predicting the onset of the fadeout. But it will be remembered that, in the days somewhat preceding the outbreak of War, certain amateurs had noted a peculiar hissing noise in their receivers when one of these fadeouts was beginning. This "hissing phenomenon," as the amateurs called it, has recently been shown to be an enhancement in the intensity of that solar noise which is more or less regularly observable on very short wavelengths, at least during the passage of a sunspot across the sun's disc. In fact, it is nothing more nor less than reception of radio energy being emitted from the sun.

It is interesting to note, however, that the noise intensity is greatest slightly before the short wave fadeout begins, though whether this is of very much value to anyone engaged in practical communication is a doubtful point. The intensity of noise diminishes, of course, because, once the ionised region has been built up, the solar radio transmission is also absorbed there, and cannot get through to the earth. We may conclude, therefore, that to all intents and purposes the Dellinger fadeout is an unpredictable phenomenon. Worse still, once it occurs there is very little we can do about it from a practical point of view. By working on the highest usable frequency, we should avoid the worst of the effects, at least during all but the most intense of these fadeouts, but, for the amateur, the best advice seems to be to sit still and wait for it to subside. Fortunately, one does not have long to wait.

The Ionosphere Storm

It is otherwise, however, with the second class of disturbance, that which is called the "ionosphere storm," for this often lasts as long as a fortnight. On the other hand, its effects are not so serious as are those of the Dellinger fadeout, though considerable disruption to short wave services does occur. The ionosphere storm seems to be due to the arrival in the atmosphere of corpuscles ejected from the sun, apparently from near the central zone of the disc. The storm seems to be connected with a sunspot on the solar disc—or possibly an M region thereon—and the offending sunspot is, therefore, often visible just past the centre when the storm starts, having moved a very considerable distance during the time interval between the departure of the corpuscles from the sun and their arrival in the terrestrial atmosphere. Their effect upon the "F" layer is so to upset its structure that its reflecting power is diminished.

During ionosphere storms, transmission will, therefore, often be better on frequencies a little lower than those on which it is best during undisturbed days, and if two frequency bands can be used for the one transmission—as is often the case with broadcast services—a certain measure of protection against ionosphere storms will result. That is not to say that reception will be as good on the lower frequency during the ionosphere storm as it is on the correct frequency during an undisturbed day. For the radio amateur, if communication on a high frequency band fails owing to an ionosphere storm, the only thing to do is to change to the next lowest frequency band and hope for the best.

It would be particularly useful, in regular communication services, if the occurrence of ionosphere storms could be predicted, but, although the subject has been under close study for some years, we cannot yet claim to be able to forecast the occurrence of a storm with very great reliability. Both magnetic and ionosphere storms tend to repeat themselves at intervals of about 27·3 days, because at those intervals, on the average, the same areas on the sun are directed towards the earth. Thus, if corpuscular streams from those areas have caused one storm, they may be expected to cause further storms, if they persist. At the time of the sunspot minimum, this 27·3 day recurrence was working very well, and very accurate forecasts resulted, but nowadays, the recurrence tendency seems upset and obscured by a mass of sunspots breaking out in different positions on the sun's disc, and giving rise to disturbances during what should be perfectly quiet periods. Then, again, a disturbance which is expected will often occur a day or so late, and as to the length of time for which it will persist, there is no reliable way of telling this at all.

There are various indications which give short-term warning of the onset of a storm. The critical frequencies are usually very high just before a storm; the earth's magnetic field often becomes highly disturbed shortly before a storm breaks out; DF bearings suffer lateral deviation early in a storm; routes traversing polar regions are affected by the disturbance before those passing through lower latitudes; a peculiar form of distortion is often observable on broadcast stations within the skip distance. So, whilst no highly reliable indication of the coming of a stormy day is possible, either on a long- or a short-term basis, the subject is well under consideration, and as time goes on we may hope to be able to forecast such storms with greater accuracy.

Conclusion

The subject of ionosphere data, and the way it is obtained and applied, is a very large one, and its study greatly facilitates the efficient planning and operation of large-scale short-wave services. There is a great deal yet to be learned, and, both in the acquisition of experimental data and in the development of the technique for applying it to practical purposes, there is plenty of room for amateur activities. There are many interesting phenomena which still require investigation—for example, the causes, geographical extent, movement, and other characteristics of "Sporadic E"—and amateurs are often in a better position than engineers to observe and report upon some seemingly unimportant happening, which may, in fact, be of the greatest scientific significance. They are not bound by the necessity of maintaining a continuous commercial service, or providing an uninterrupted broadcast programme, as is the engineer, and thus the scope of their observations is less restricted.

Information secured by radio amateurs has often, in the past, proved of great value in the investigation of certain phenomena, and in the enlargement of the general field of scientific knowledge. And it has also, ultimately proved to be of great help in the ordinary day-to-day work of the short-wave engineer.

Reliability

A growing number of amateurs are using RG1-240A's in their 'modulator' and 'final' power supply units. And there is much to commend this half-wave mercury vapour rectifier. Its life expectation is well above average; it has the advantage of a constant and small voltage drop; the use of zirconium reduces positive ion bombardment of the cathode; every valve is subjected to rigorous back-arc tests; its price is 20/-.

Here are a few notes which will help users to get the best from this very reliable valve. The use of correct filter circuits and the careful observance of the operating rules are essential if maximum life is to be obtained.

Characteristics

STATIC

Vf	4.0V
If	2.7A
Peak Inverse Voltage	4.7KV
Peak Ia	1.25A
Average Ia	250mA
Valve volts drop	16V
Ambient temp.	0–50° C.
Base—British 4-pin.	

DYNAMIC

Circuit	Output	Input	Filters	
			L. in H	C. in μF
Single phase full wave	1500V 500mA	1670V rms per valve	4.5	4
	1000V 150mA	1120V rms per valve	10	4

Filter Circuits

The values of L and C quoted in the table are for the specific output currents stated. For operation under alternative conditions these values must be re-calculated. L should vary in direct proportion to the effective load resistance:

$$L = \frac{\text{Reff}}{940} \qquad \text{(input at 50 cycles)}$$

or, to allow safety factor,

$$L = \frac{\text{Vout}}{\text{Iout}} \times 1.5 \text{ (L in henries; Vout = required voltage; Iout = current in mA)}$$

provided C remains constant at 4 μF.

e.g.—For 1000V at 100mA, $L = \frac{1000}{100} \times 1.5 = 15$.

If the ripple is too great and C has to be increased, then L must increase in direct proportion. Conversely, L may be reduced in direct proportion to any reduction in C.

If a double filter is used the values in the first section must be the same as those for a single filter.

Condenser filter input circuits must not be used or the peak Ia will be exceeded.

Operating Rules

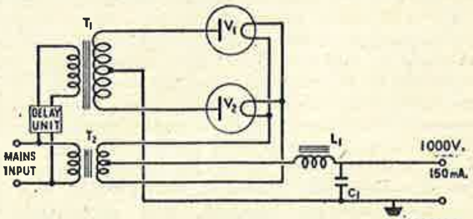
After transportation, all mercury vapour valves must be run-in without H.T. for at least 30 minutes in order to remove mercury from the electrodes. In normal use, the filaments must be run for at least 60 seconds before H.T. is applied, to avoid cathode sputtering.

Recommended Circuits

Final or P.A. Supply (suitable for use with a QY2-100 or 813).

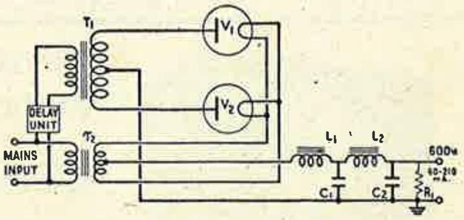
Modulator Supply (approx. 0.25% ripple) (suitable for use with 2 QV05-25's or 807's).

FINAL or P.A. SUPPLY



V_1, V_2, RGI-240A. T_1, 1200-0-1200V/150mA. T_2 2-0-2V/6A
L_1, 5-25H Swinging Choke 250/50mA. C_1, 4μF.

MODULATOR SUPPLY



V_1, V_2, RGI-240A. T_1, 750-0-750V/250mA. T_2, 2-0-2V/6A.
R_1, 15000 ohms 25 watt. L_1, 5-25H Swinging Choke 250/50mA.
L_2, 20H/250mA. C_1, C_2, 4μF.

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MVT.21

Velocity Modulation Tubes for Centimetre Wave Communications*

By A. F. PEARCE†

Introduction

VELOCITY modulation tubes may be used as oscillators, amplifiers, and mixers. The waveband for which they are most suitable is approximately from 2,000 to 10,000 Mc/s., or, in terms of wavelength, from 15 to 3 cm. Wavelengths of this order are very convenient for radar purposes, since it is possible to employ highly directive beams using an aerial of moderate size. Consequently, although velocity modulation was in its infancy in 1939, much development was carried out both in this country and in America during the war.

Owing to the fact that, for radar purposes, pulsed transmission has hitherto been used almost exclusively and that the magnetron has been found very suitable for the transmitter, research on velocity modulation valves has been largely confined to providing a low power CW oscillator to act as a beating oscillator in the receiver. Consequently little work has so far been done on high power CW valves, either as oscillators or as amplifiers.

The principle of velocity modulation was first put forward by A. and O. Heil in 1935, and applied to an oscillator at a wavelength of about 20 cm. In 1939. much improved oscillators for shorter wavelengths were devised by Hahn and Metcalfe, and by R. H. and S. F. Varian. The latter workers used hollow resonators, which they called rhumbatrons, the whole oscillator or amplifier being termed a klystron.

Before describing the principle of the klystron perhaps it will be appropriate to comment on the failure of conventional valves of the triode class at very high frequencies.

Failure is due to the fact that electrons take a finite time to pass from the cathode to the grid. In a conventional triode this time is of the order of 10^{-9} of a second, which is negligible compared with the periodic time of an oscillatory potential applied to the grid, if the frequency does not exceed a figure of about 100 Mc/s. The current drawn from the cathode thus faithfully follows the voltage impressed upon the grid. At higher frequencies however this is not the case. The alternating voltage on the grid may change appreciably during the transit of the electron between cathode and grid. It may even reverse its sign. It is evident that under these conditions the current will not follow the grid voltage, and the valve becomes less and less efficient as the frequency is increased. By reducing the grid-to-cathode spacing within the valve, the frequency range may be increased, but there are clearly limits to this process. The limit appears to have been reached in triodes of the grounded grid type, which may be used as oscillators at 10cm., although the efficiency is falling rapidly in that region.

Principle of Velocity Modulation

Velocity modulation makes use of transit time effects to produce a charge density modulation of the electron beam. The principle is most easily understood in the case of a velocity modulation amplifier (Fig. 1). G1 and G2 are a closely spaced pair of grids between which is connected a resonant circuit LC, tuned to a frequency f. This is the " buncher." Some distance away is the " catcher," which consists of a similar pair of grids, G3 and G4. with a similar circuit also tuned to the same frequency f. G2 and G3 are connected together and to a source of potential V_o, the negative end of which is connected to the cathode of an electron gun. The electron gun projects a beam of electrons through both sets of grids, the beam being finally collected in the collecting electrode or anode, which is usually run at the same potential as the grids.

Suppose now that the buncher circuit is coupled to a source of high frequency power of frequency f. A sinusoidal voltage, such as that shown in the lower figure, will appear between G1 and G2. This will accelerate electrons passing through during the positive half of the cycle and will decelerate those during the negative half. Some electrons, such as the ones represented by A and C, will be unaffected. Consequently, electrons emerge from G2 with a range of velocities; the beam is then said to be velocity modulated.

Now the space between G2 and G3,—called the " drift space :"—is field free, so that each electron traverses it with a uniform speed equal to that with which it leaves G2. It is easy to see that the charge density soon becomes non-uniform. Consider the

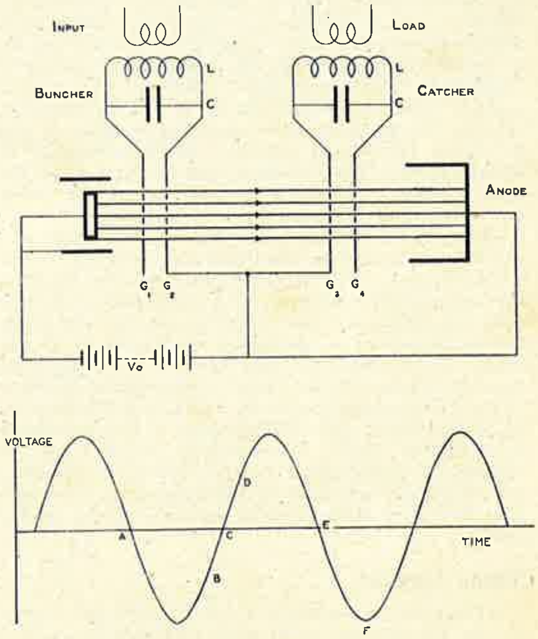

Fig. 1.
The Velocity Modulation Amplifier Circuit used by the author to describe basic principles.

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† E.M.I. Research Laboratories, Ltd.

* *An abridged version of a paper read to the Society at a Meeting held on November 15th, 1946, at the Institution of Electrical Engineers, London.*

electrons represented by B, C and D. The electron C has its velocity unchanged by the buncher. B will be retarded, but it passes through the buncher slightly earlier than C. Therefore, in moving along the drift space the two get closer and closer together, until, after a certain time, they are equidistant from the buncher. The electron D is accelerated, but starts later than C and so catches up on it just about when B and C coincide, so that, at a certain distance from the buncher, all three electrons pass by together. Electrons which start at other parts of the cycle centering on C—that is between A and E—behave somewhat similarly, so that, at a certain distance from the buncher, the electrons pass by in bunches once in every cycle. The electron density is high in the bunch and low between bunches. Thus we see that the mere drifting of the electrons in the drift space converts the velocity modulation into a charge density modulation. If now we place the catcher at the point of high charge density, resonance will occur (since the catcher is tuned to the frequency of the repeating bunches) and the catcher circuit will be set into oscillation.

It will be noticed that owing to the high mean velocity of the electrons, the transit time problem, which is the limiting factor in the case of triodes, is largely removed.

In order that the energy transferred to the catcher shall be maximum, the bunches must pass through at the instant when the high frequency voltage between G3 and G4 is at its maximum value and in the direction which retards the electrons. The phase of the oscillation in the catcher will automatically set itself so that this condition is satisfied. The exact phase relationship between buncher and catcher depends upon the drift length and the average electron velocity, which in turn depends upon the input voltage, V_0. This phase relationship is not of importance in an amplifier, but is of more importance in an oscillator, as will be seen later on.

Very little energy is required to bunch the electrons. In the ideal case we have been considering, it is zero, but in practice a certain amount of energy is lost in the resonant circuit, and some is absorbed by the beam. In a well designed amplifier this is small compared with the energy given up to the catcher, or, in other words, the high frequency input power is amplified. The power may be fed into a load in a manner similar to that employed in the buncher circuit. In practice, power gains of between 5 and 20 times have been achieved at wavelengths of about 10 cm. The efficiency, that is, the ratio of the high frequency power in the load, to the DC input power, is about 20 per cent.

The picture so far presented of bunching and catching is a rather simplified one. Owing to the sinusoidal nature of the buncher voltage, the bunches are not perfectly sharp. One effect of this fact is that the efficiency can never reach 100 per cent. but is limited to a theoretical maximum of 58 per cent. Mathematically, the bunched beam may be regarded as an infinite series of alternating currents of the fundamental frequency f and all its harmonics, $2f$, $3f$, $4f$ and so on. The intensity of the harmonics is relatively high. Consequently, if we tune the catcher to a harmonic of the buncher frequency, an output of the higher frequency may be obtained. The device is then working as a frequency multiplier.

Tuned Circuits

At centimetre wavelengths inductances and capacities of the ordinary kind cannot be used, because of excessive resistive and radiative losses. Instead, hollow resonators, usually made of copper, are used. These may have a variety of shapes.

The particular shape used by the Varians is shown in Fig. 2 (a) but a more common shape is that shown at (b). Generally, the resonator is of toroidal form, and has a re-entrant portion at the centre. The electron beam crosses the resonator through two apertures, across which there are usually grids to confine the high frequency field within the resonator. The purpose of the re-entrant portion is to allow the electrons to cross the gap in a length of time which is only a small fraction of that of a cycle of the oscillation, so that the magnitude of the electric field across the gap does not change appreciably during the electron transit. Such a resonator may be thought of qualitatively as consisting of a capacity at the centre, across which is connected a single-turn inductance. The high frequency field is confined to the interior, thus eliminating radiation loss, and the copper loss is low, so that a high Q and a high shunt impedence are obtained. The later in particular is very desirable in a klystron. The electric field, which is approximately parallel to the axis throughout the resonator, is strongest at the centre and falls off to zero at the periphery, whilst the magnetic field, which is circumferential, increases towards the outside. It is not essential to have grids in a resonator if the apertures are small enough and the beam voltage high enough.

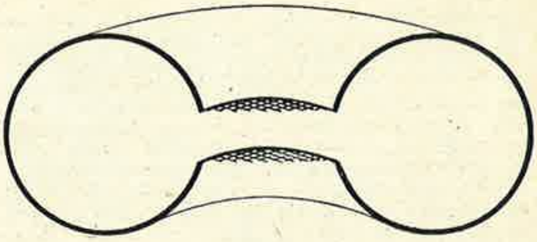

Fig. 2 (a).

Hollow Resonators are used instead of the usual inductances and capacities at centimetre wave-lengths. The illustration shows a form developed by the Varians.

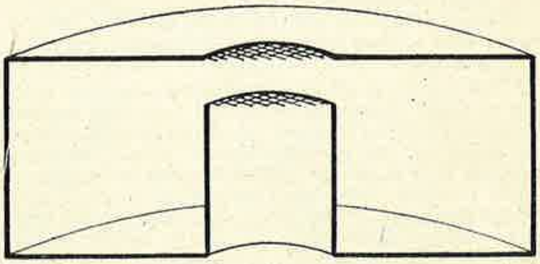

Fig. 2 (b).

Shows a more usual form of Hollow Resonator.

In order to couple to a resonator of this kind it is usual to insert a loop which couples with the alternating magnetic field within the resonator. This loop is connected to a balanced pair or more usually to a co-axial line, along which the power is fed. If it is desired to feed power into a wave guide, this may be done by cutting a slot in the resonator wall and attaching it to the end of the waveguide.

The Klystron as a Self-Oscillator

Clearly, all we have to do to the amplifier to make it oscillate is to feed back a portion of the energy of the catcher into the buncher, in the correct phase. This may be achieved by means of a coaxial line as shown diagrammatically in Fig. 3.

Very often the drift-length required is such that the resonators may be placed back-to-back. Coupling is then quite easy, by either of two methods. The first is to have a single loop partly in each resonator and passing through a hole in the common wall. The second is by means of a slot or slots in the dividing wall. This allows the magnetic field of one resonator to couple with that of the other.

When resonators are directly coupled in this way, there is a definite phase relationship between the voltage across their gaps. In fact they are either in the same phase or in opposite phases. Referring to Fig. 1 again, if the resonators are in phase a bunch, the centre of which passes through the buncher at C, must, in order to give up energy, pass through the catcher at time F, or any whole number of periods later than F. Hence the transit time must be $\frac{3}{4}$ of a period, or $1\frac{3}{4}$ periods, or $2\frac{3}{4}$ periods, and so on. If the resonators are so coupled as to be out of phase, the transit time will be $\frac{1}{4}$, $1\frac{1}{4}$, $2\frac{1}{4}$, etc. periods. In either case, it is clear that, since the length of the drift space is fixed, there is only one voltage that will satisfy the phase condition for each mode. Hence a velocity modulation oscillator will operate only at a series of discrete voltages.

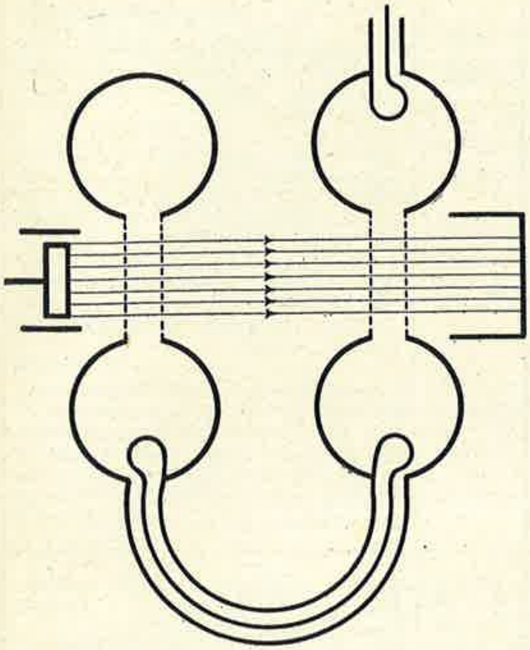

Fig. 3.

A klystron may be made to self-oscillate by feeding-back a portion of the energy of the catcher into the buncher. The diagram shows how this can be done by means of a co-axial line.

The load, too, must be correctly adjusted if there is to be a maximum transfer of power to it. This may be done either by moving the loop, or, if the loop is fixed, by suitable matching in the line leading to the load.

Klystrons

The CV80 is an example of a klystron oscillator, designed for a wavelength of 6·95 cm. and the CV81 for 7·4 cm. The nominal input is 6 kV 250 mA, and the high frequency output is 100 to 300 watts, giving an efficiency of 10 to 20 per cent. Most of the valve is made of copper, and it is the usual practice to earth the resonator and anode, and to have the cathode at a negative potential.

Reflection Oscillators

So far, only velocity modulation valves having two resonators have been mentioned. It is evident that a single resonator can be made to serve as both buncher and catcher by reversing the direction of the electrons after the first transit, so that they traverse the resonator a second time in the opposite direction. The principle is shown in Fig. 4.

Usually the electrons are reversed by means of a reflecting electrode, R, which is held at a negative potential with respect to cathode. In that case, deceleration occurs after the electrons leave the resonator, and they are reflected from a plane somewhere between the resonator and the reflector. The reflector is so shaped that the electrons are focussed back through the resonator aperture and not allowed to spread laterally.

The most important advantage of having only one resonator is that the tuning of the oscillator is much simplified, since there is then no problem of tuning two resonators to the same frequency, as in the klystron. A disadvantage is that the efficiency obtainable is approximately halved. That is not, however, of much importance in the usual application of reflection oscillators, which is to act as beating oscillators in superhet receivers. Using a crystal mixer, a power of some 20 to 100 milliwatts only is required for this purpose, and this is well within the capabilities of a reflection oscillator.

In a reflection oscillator, the phase condition is a definite one, since the buncher and the catcher are one and the same. Bearing in mind that the second transit is in the reverse direction, we find that the transit time must be $n + \frac{3}{4}$ periods for usual shapes of reflecting fields, where n is an integer. There are now, however, two voltages that can be used to satisfy this condition, namely the resonator voltage, V_0, and the reflector voltage, V_R. Usually it is easier to vary the reflector voltage and to leave the resonator voltage fixed. The effect of this is to vary the distance traversed by the electrons before reflection. At certain values of the reflector voltage the distance is such that the transit time condition is satisfied. Oscillations are then obtained. Hence, as we vary the reflector voltage from zero upwards, we pass through the various modes in decreasing order. The efficiency is not, of course, the same in all modes, and may be zero in some of them.

Electronic Tuning

Another property of reflection oscillators is that their frequency may be controlled to a small extent

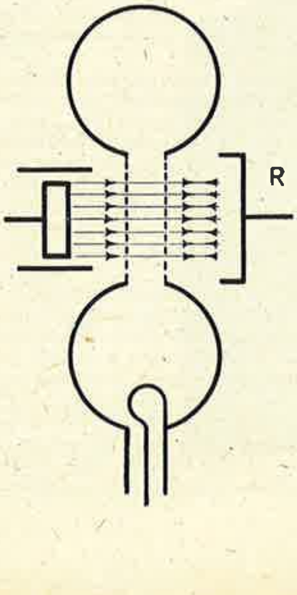

Fig. 4.

Illustrates how a single resonator can be made to serve as both buncher and catcher by reversing the direction of electrons after first transit.

by electronic means. If the reflector voltage is such that the transit time condition is satisfied, then the oscillating frequency is the natural frequency of the resonator. If, however, the reflector voltage is slightly different from the optimum value, then the electron bunches arrive at the resonator gap slightly out of phase with the voltage across it. In other words, the bunched beam presents a reactive impedance to the resonator in addition to the usual resistive component. Now, in any oscillating system, the total reactance is zero; hence, if oscillation is to occur, this reactive component of the beam must be neutralised. This can be done by the resonator if it oscillates at a frequency other than its true resonant frequency. The net result, therefore, is that the frequency of oscillation changes. Thus, as the reflector voltage is varied through the region of optimum output, the frequency changes continuously. Of course, the power output decreases on either side of the optimum, eventually dropping to zero. The magnitude of the frequency change that may be produced depends upon various factors of the valve design, prominent among which are the loaded *Q* and the geometry of the reflecting field. It is usually greater in low voltage than in high voltage tubes. At a wavelength of 10 cm., the magnitude of this frequency change is about 20 to 30 Mc/s.

This property of the oscillator is useful for Automatic Frequency Control, and has been so used in radar receivers. It is not uncommon for the frequency of the transmitter to vary appreciably, especially if it is a magnetron, owing to changes of impedence at the antenna due to scanning, or for other reasons. If this happens, for efficient reception by the superheterodyne method, the beating oscillator of the receiver must also change frequency by the same amount so as to maintain a beat frequency of 30 Mc/s., or whatever frequency is chosen as the intermediate frequency. This may be brought about by arranging tuned circuits in the I.F. stage to generate a voltage, the magnitude and sign of which depends upon how far and in what direction the intermediate frequency has departed from the specified value. This voltage is applied to the reflector of the oscillator, thus changing the frequency until the intermediate frequency is restored to its nominal value. Quite rapid changes of signal frequency may in this way be followed.

Co-Axial Line Oscillators

This type of velocity modulation oscillator uses a co-axial line as a resonator. The line will resonate when its effective length is an odd number of ¼ wavelengths. In practice only the ¼ and ¾ wavelength modes are used.

In order to allow an electron stream to pass through it, the cross section of the line is modified at a point a ¼ wavelength from its closed end. The outer conductor is turned in to form fins, and the inner conductor is flattened to form a channel, through which the flat, sheet-like beam can pass. In this way two gaps are formed, in each of which the electric field is intense and localised where it intersects with the beam. The beam is formed by an electron gun consisting of a cathode, a "control grid" and a "screen grid" which acts as the primary accelerator. The beam, after its passage through the co-axial line, is caught on a collecting anode. In order to focus the beam, a magnetic field is necessary, and this is provided by a small permanent magnet surrounding the valve.

The mode of action is similar to that of any two-gap klystron. The first gap acts as the "buncher," modulating the velocity of the beam. The inner conductor acts as a field-free "drift-tube" in which the velocity modulation is converted into electron density modulation by the well-known formation of bunches, whilst the second gap acts as the "catcher." Three such valves are mentioned in the table below.

Practical Examples

The following table gives a summary of some V.M. valves:

Type	Description
CV35 CV36 CV37	Reflection oscillators. Wavelength range covered 8·8 to 11·0 cm. Input 1300 volts, 7 mA. Reflector —300 volts. Output 0·3 to 0·5· watt. Focussing electrode around cathode can be used as an amplitude control, for modulation purposes. Frequency stable type.
CV116 CV237 CV238 CV272	Low voltage oscillators. Wavelength range covered 8·3 to 11·0 cm. Similar construction to CV35 series, but with larger apertures, and with grids. Input 250 volts, 30 mA. Reflector —100 to —150 volts. Output 0·2 watts. May be used for AFC or frequency modulation, because of electronic tuning range of about 30 Mc/s. Used mainly as beating oscillator.
CV234 CV228 CV230	Co-axial line oscillators. Wavelengths 8—16 cm., 6—7 cm. and 9·75—10·15 cm. respectively. CV234 and CV228 are frequency stable type. CV230 is designed for electronic tuning, and has a tuning range of 20 Mc/s. All work at 250 volts and give an output of 0·5 watt.
CV87 CV129	3 cm. oscillators. High voltage, frequency stable types. Output about 150 milliwatts.
CV322	3 cm. oscillator, with resonator within envelope. Low voltage type, for electronic tuning. Output 60 milliwatts.

Applications

The tabulated list of oscillators is not exhaustive, but it includes some of the principal types that have been developed in this country.

Very little has been said about amplifiers, because oscillators are at present most likely to be of interest to amateurs, and because amplifiers have not yet been developed to any great extent. As already mentioned, klystron amplifiers have been made both for power amplification and for low level amplification of weak signals. In the latter case, it has been found that such amplifiers have excessive noise, and are therefore not very useful. Velocity modulation mixers have hitherto suffered from the same defect.

Coming now to the application of oscillators to the communication of intelligence, the available methods may be divided into three broad classes. The first two, which apply to CW transmission, are amplitude modulation and frequency modulation; the third is pulse modulation. The latter will not be discussed here.

With regard to amplitude modulation, the two principal ways of doing this are by variation of the resonator voltage or by variation of current. The former involves change of input power in the klystron, which has to be supplied by the modulating signal, either directly or after amplification. Consequently, current modulation at constant resonator potential is preferred. Most of the oscillators described are provided with a grid which may be used for this purpose, and it requires no power. Some frequency modulation invariably accompanies this amplitude modulation, but if a frequency stable oscillator of the high voltage type is used, this is not excessive. For instance, in the CV35, the grid-swing required for 100 per cent. modulation is about 30 or 40 volts, and the frequency change is only one or two Mc/s. For higher powers, the klystron CV80 requires a grid-swing of several hundred volts, and has a frequency shift of 3 Mc/s. or less.

Frequency Modulation

For frequency modulation, a low voltage reflection oscillator is most suitable. As we have already seen, frequency changes of up to 30 Mc/s. are available, and the rate at which the frequency changes with reflector voltage is about one Mc/s. per volt. If the full frequency range of 30 Mc/s. is used, the amplitude will fall to approximately one-half at each extremity but for a frequency modulation of only a few Mc/s. the amplitude change is small.

Suitable oscillators for frequency modulation transmitters are the CV116 class and the CV230 in the 10 cm. band and the CV322 in the 3 cm. band. No valves giving appreciably greater powers than these are at present available.

Conclusion

From this review it would appear that for reception purposes, there is a reasonable choice of beating oscillators for wavelengths in the region of 10 cm. and also at about 3 cm. It has recently been announced that a wave band from about 12·3 to 13 cm. (2300—2450 Mc/s.) has been allocated for amateur use. In this connection it may be of interest to note that the operating wavelength of the high voltage oscillator CV36 and of the low voltage oscillator CV272 may be increased by fitting a larger resonator than the one provided.

On the transmission side, for CW purposes, one is at present limited to the same oscillators apart from the fixed frequency klystrons CV80 and CV81. Useful ranges of 30 to 40 miles have, however, been reported on powers of less than half a watt, using 30 inch paraboloids. In the Radiolocation issue of the *Journal of the I.E.E.* Megaw reports transmissions over distances of up to 200 miles at 9 cm. on a power of 0·6 of a watt, and over a 57 mile link at 3 cm. using a reflex oscillator of 150 milliwatts output. In both cases 4 ft. paraboloids were used.

Acknowledgements

The author wishes to thank the British Thomson-Houston Company Ltd. and Standard Telephones and Cables Ltd. for their co-operation in supplying information concerning some of the oscillators and also Mr. I. Shoenberg, Director of E.M.I. Research Laboratories, Ltd., for permission to publish this paper.

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(1) "*The Development of Radio Valves,*" J. H. E. Griffiths: *J.I.E.E.*, Vol. 83, Part IIIA, No. 1, 1946, p. 173. This paper gives among other things a broad survey of centimetre wave valves.

(2) "*Velocity Modulation Valves,*" L. F. Broadway: *J.I.E.E.*, Vol. 93, Part IIIA, No. 1, 1946, p. 183. This paper is a short survey of centimetre wave valves. Further details are given in a recent paper by Broadway, Milner, Petrie, Scott and Wright in the *J.I.E.E.*, Vol. 93, Part IIIA, No. 5, 1946, and in other papers in the *J.I.E.E.*

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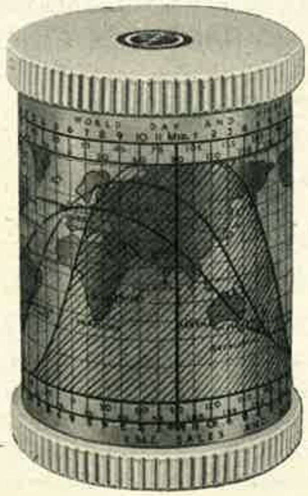

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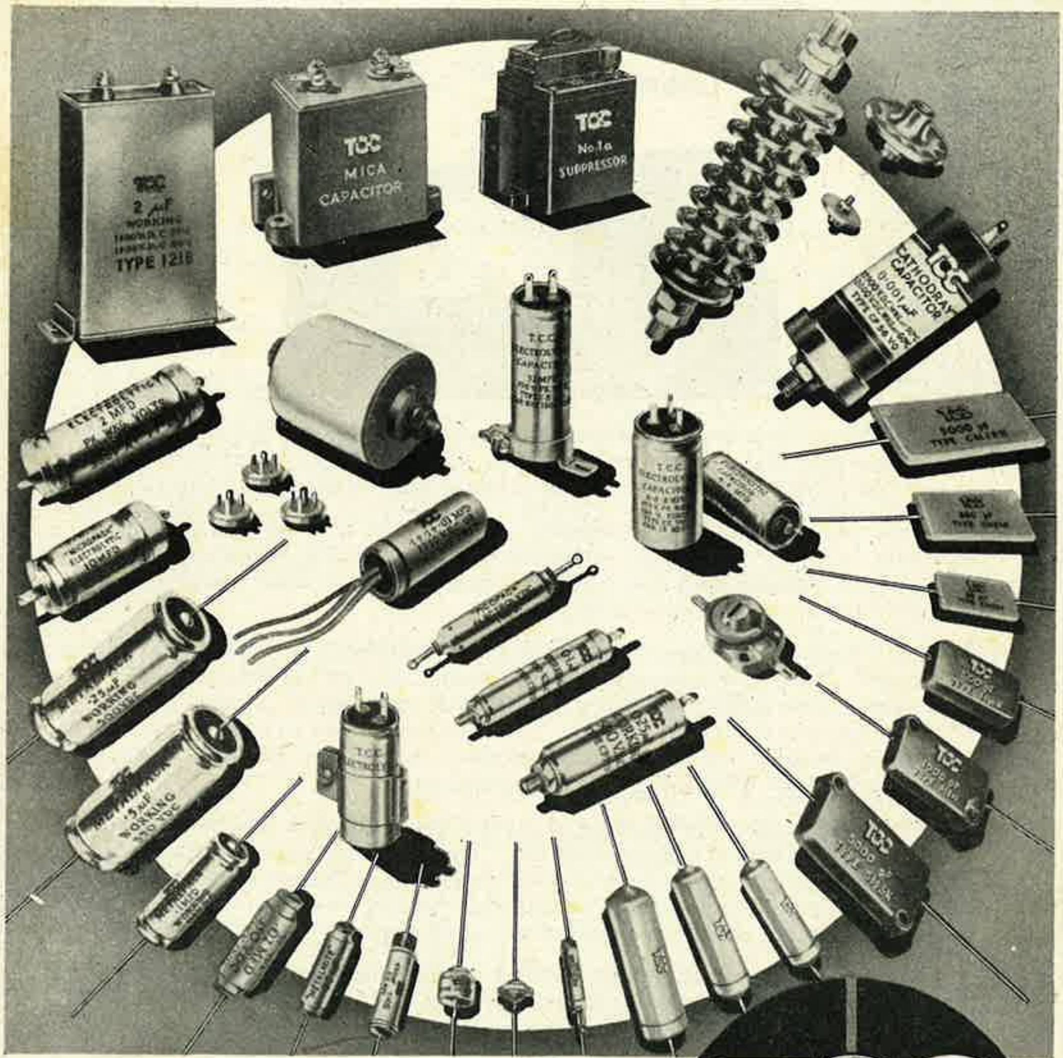
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