Propagation of Long Radio Waves

Part 1

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THE MAIN PURPOSE of this article is to present textbook-type information on the basics of propagation on frequencies between 100 kHz and 200 kHz. Why should people be interested in such an unusual and restricted band of frequencies? Basically because some amateurs in several parts of the world have operated in this region, and if an amateur band is ever allocated in the low-frequency spectrum, it is in this region that such a band would be allocated. Therefore, it is important that interested persons should understand operating conditions on these frequencies.

For some time now, I have been thinking of presenting this article on the subject of low frequency or long wave propagation, but have been deterred somewhat by the difficulty of presenting a clear overall picture. This difficulty is not helped by the apparent lack of suitable references to fill in the picture. I have come to the reluctant conclusion that a lot of gaps in knowledge do exist in the subject, and I will point these out at the end of the article.

As far as I know, no attempt has ever been made before to explain LF propagation in concise terms with the average interested reader in mind, and to point out where it differs from HF propagation. It is, therefore, hoped that this article will become a basic reference for amateur radio on the subject of LF propagation.

There is an enormous amount written on the subject of HF propagation for both the amateur and the professional. This is very well presented for the amateur in texts such as the ARRL Handbook and many others. The subject of LF propagation has been around for a long time, and is covered in great detail in technical books and papers on the subject, but is not covered in amateur radio texts.

Part 1: The Basic Physics of Propagation

Introduction

Propagation of electro-magnetic waves from the longest radio waves through to light waves is affected by the same physical laws, but the physical nature of the media through which the waves pass varies with frequency. The differences are brought about by many different factors, for example, the inertia and movement of charged particles in the ionosphere when acted upon by fields of different frequency.

Propagation of low frequency or long electromagnetic waves (long radio waves) is dependent upon surface waves and, as with HF, waves reflected between the ground and the ionosphere, but their play in the propagation process is quite different from that at the high frequencies. At low frequencies the combined effect of ground and ionospheric reflections results in a wavefront at the surface of the earth similar in character to a surface waves, as we shall see later. This similarity has given rise to the popular misconception that *"low frequencies propagate around the earth by ground wave propagation"*.

In general, the propagation of low frequency radio waves is quite different from high frequency. In fact there is nothing similar in any bands at present held by amateurs. Even propagation at 160 metres is more similar to HF than LF. There are many misconceptions about LF propagation, and it is intended to explain all these things here.

Basic Concepts

In this article it is proposed to use the "light" analogy frequently. Reflection and refraction at light frequencies are exactly the same as at VHF, HF and low frequencies — only the scale changes. To put the two in real terms, the wavelength of red light is a little less than one micron or 10^{-12} metres. In frequency it is about 400 terahertz or 400x 10^{12} Hz. This is about 30,000,000 times the frequency of 14 MHz.

Electromagnetic waves at any frequency normally propagate in straight lines, but are bent around curves by the process of reflection, refraction or diffraction. These three processes are the basis of radio propagation.

For the purpose of this article, I refer to HF as the band of frequencies mainly between six and 30kHz, and I refer to LF as the band of frequencies mainly between 10 and 200kHz. Ten to 30kHz is correctly VLF, but in this article I use the term LF or low frequency — a general term covering the general type of propagation to be described.

Refraction

This process is well known to anyone who has studied physics at school, so the effects will be described briefly. An electromagnetic wave of any frequency will travel slightly slower in a medium, such as air, than it will in a vacuum. The amount by which a wave front is slowed down in a medium is dependent upon its "refractive index". In light, this is also known as "optical density", but the process is the same at radio frequencies as at light frequencies. In general, the higher the actual density the higher the refractive index. A vacuum has a refractive index of one, air has a refractive index of around 1.0003. Substances like glass or water are much higher. Cold air has a slightly higher refractive index than warm air. *Refractive index is directly related to permittivity or dielectric constant* and this is particularly important in respect of the ionosphere, as we shall see later.

The effect of a wave front, travelling

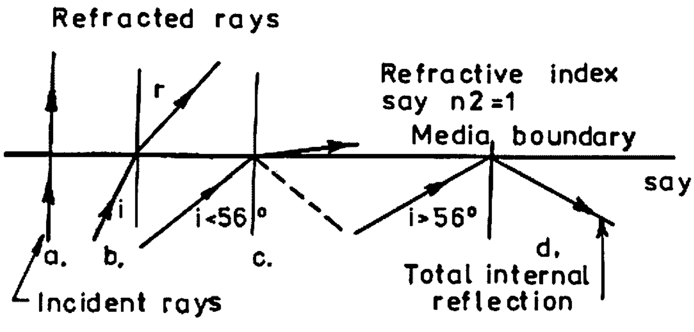

FIG. 1

through a plane that separates media of different refractive indices, is that the wavefront will change its direction at the plane. This is illustrated in Figure 1. When there is only a small change in refractive index, substantial bending will take place only when the direction of travel of the wave front has a small angle to the plane. Examples of refraction of light are well known. In radio there are many examples of refraction. Some examples are bending of VHF waves when they cross a cold front (HF waves are similarly affected although the effect is not as noticeable). Another example is that of the atmosphere, which decreases in pressure and hence refractive index (although the change is very small) with height, and this has the effect of making the horizon distance look farther than in a vacuum. Yet another example of refraction in radio would be the bending in direction of an HF wave as it passes through the ionosphere, as shall be discussed in some detail below.

The bending that takes place when an electromagnetic wave passes from one medium to another is based on the formula —

$$\frac{\sin i}{\sin r} = \frac{n_2}{n_1} \qquad (1)$$

where i is the angle of incidence and r is the angle of refraction, n_1 is the refractive index of the first media, and n_2 is the refractive index of the second medium.

It is important to note that, when dealing with bending of a wave direction at a change of refractive index, the change does not have to be at a plane surface. If the change in refractive index is gradual over a distance, then the bending will take place gradually. This will be dealt with in more detail under total internal reflection.

Reflection

Reflection has taken place at a plane, or virtual plane, when the wave front travelling towards the plane at an angle to the perpendicular, or normal to the plane, is turned (or reflected) away from the plane at the same angle to the normal. "The angle of incidence equals the angle of reflection" (see Figure 2). Also the incident ray, the reflected ray and the normal to the surface at the point of reflection all lie in the same plane and on the same side of the surface. If the surface is uneven and the irregularities are large as compared with a wavelength, the wave front will be reflected in several directions at once, resulting in "scattering". A poorly reflecting surface can result in "loss".

There are two basically different types of reflection.

1. Reflection that occurs at a plane surface is known in physics as "regular or specular reflection" and which we will refer to here as "plane surface reflection".
2. Reflection that occurs when a wave travels from a medium of high refractive index towards a medium of lower refractive index. This process is known in physics as "total internal reflection".

There are numerous examples of both these types of reflection in of radio waves, as we will see in the article.

1. Plane Surface Reflection

This, too, can be divided into two basic types, they are:

1. Reflection at a plane metallic surface. There are no examples of this in nature, but there are plenty of man-made objects for both radio and light using metallic reflectors. These are very familiar to the average amateur and require no explanation.

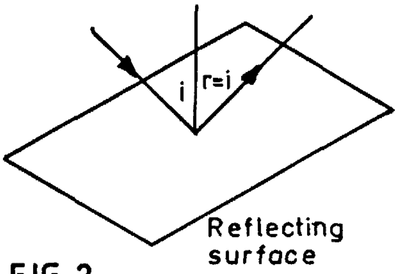

FIG.2

2. Reflection at either a dielectric surface or a lossy resistive surface. In order for useful "regular" reflection to take place several properties are required. There must be a surface or discontinuity between the two media. Irregularities on the surface must be small as compared with a wavelength; the smaller the irregularities the better the reflection. Conversely, the lower the frequency the better the reflection. The change or discontinuity between the propagating medium and the reflecting surface should be as sharp as possible. That is, a discontinuity which consists of a gradual change in refractive index over many wavelengths will not produce regular reflection, but it may produce total internal reflection, as we shall see shortly. The sharper the discontinuity the better the reflection. The greater the change in dielectric constant or, in some cases, magnetic permeability (both affect refractive index) and/or conductivity the better the reflection. The lower the angle of the incident ray to the discontinuity surface the better the reflection. Reflection can take place when the discontinuity is either of higher refractive index or lower refractive index than the medium of the incident wave. When reflection takes place, only part of the wave is reflected. Some is lost and some may pass through the surface and propagate in a different direction (refraction).

Reflection at plane surfaces is easy to see with light. When light strikes the surface of a plane sheet of glass with an unsilvered surface, the light is better reflected at a low angle to the surface than at a high angle, and not all the light is reflected. Some passes through the glass. If the surface of the glass is rough, scattering takes place and less light is reflected. A similar effect is observed if the surface is dirty. If the surface of the glass was not hard but slowly merged into the air similarly, reflection would be reduced or eliminated. This is not easy to demonstrate with glass, but the effect is very important when dealing with atmospheric and ionospheric effects. An important point to note is that a plane reflector can have quite a poor surface and, in fact, have practically no reflective effect for a vertical incident ray but have quite a good reflective property at a very low angle.

In radio, the best example of plane surface reflection of this type is the reflection of radio waves by the ground, and this displays all the properties listed above. Sea water, which has a higher dielectric constant and better conductivity than soil, is also a better reflector. In fact, water will reflect all waves from radio to light frequencies. Soil will only produce *regular* reflection at radio frequencies where the irregularities are small compared with a wavelength, hence the longer the wavelength (the lower the frequency) the better the reflection.

2. Total Internal Reflection

This form of reflection is a direct result of refraction. In some amateur articles recently it has incorrectly been referred to as refraction. The term is, therefore, a bit misleading. It differs from ordinary refraction or just bending in that the wave is turned around completely and comes out of the reflecting medium at the same angle as it entered. It fulfils all the requirements of reflection given above. See Figure 1. Total internal reflection takes place if the sine of the angle of incidence times the ratio of the refractive index of the first medium to that of the second is greater than 1.

In mathematical terms, and by transposing formula 1:

$$\text{if} \quad \frac{n_1}{n_2}\sin i > 1$$

then sin r is greater than 1. There is no angle for a sine greater than 1 and r is unreal — reflection then takes place.

As a simple example of the above, suppose n_1=1.2 and n_2=1. Then, if the angle of incidence i=30° (60° to the surface), the angle of refraction r=36.8°. If i=60° (30° to the surface), sin r=1.04. Refraction cannot take place and the wave is reflected (see Figure 1). The critical angle occurs when sin i=1/1.2, therefore i=56°.

The old physics term of "total" internal reflection is based on the notion that this reflection takes place inside the higher density media and is not caused by the surface. It is, therefore, lossless. The term "total" is slightly misleading. The reflection loss may in theory be zero but the media through which the electromagnetic wave passes certainly may be lossy.

Total internal reflection, which is the direct result of refraction, differs from plane surface reflection in several major ways. Total internal reflection takes place only when a wave moves from a medium of higher to one of lower refractive index. Like refraction, this reflection can take place over a considerable distance where the refractive index changes very gradually. This is completely different from plane surface reflection as described above. In the case of the ionosphere, bending and ultimate reflection may take place over a distance of thousands of wavelengths; see Figure 3. (If the boundary between the two media is sharp and the angle of incidence is too small for total internal reflection, plane surface reflection and refraction may take place, see the dotted line in Figure 1c.

An example of light being reflected by this process at a diffuse surface would be that of a mirage or reflection from heat haze on a road. This is the same as reflection of VHF radio waves from a temperature inversion.

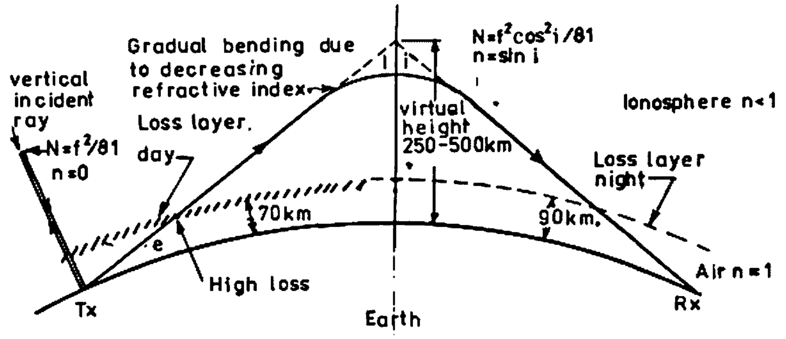

FIG. 3 HF Ionospheric reflection

Diffraction

In some ways this is the most mysterious characteristic of propagation, but it is certainly very important at low frequency. It is a characteristic of all wave motions (even waves on water) that you cannot have a sharp edge to a wave beam. If you try to, the edge of the wave pattern will generate new waves which, in effect, causes the beam to "spread out". The theory is that every point on the edge of a beam (of light, radio waves or even ocean waves) acts as new source of waves. The sum total of all these sources is to produce a beam that spreads out at the edges.

The effect is observed when light is projected at a very small hole; the hole will tend to become a source of light. Another example would be where a laser beam is projected at the moon — the spot on the moon is a lot larger than would be expected from the radiation pattern of the source. On an ocean island, waves come in on every side of the island even though the waves out at sea may be travelling in one direction. In radio, waves bend beyond the horizon, and this is the basis of ground or surface waves. The larger the wave the bigger the corner the wave will bend around. In other words, the effect is a matter of scale.

This effect therefore becomes more significant the longer the wavelength, and will be dealt with particularly under low-frequency propagation.

(To be continued)

The Marconi Spirit

Some years ago, Dr W A S Butement VK3AD told me the following story during a business trip to the WRE in VK5. (VK3AD is now an SK).

Bill was studying in London, going for his PhD when he had regular CW QSOs with his high school friend in Wellington, who was the son of the then Prime Minister of ZL.

His friend asked Bill one day to go to the House of Commons in London and observe the debate on a certain matter, which would be of great importance to his father, and if he could obtain and pass on the information via QSO before anyone else in ZL could have it.

Bill did as asked by his friend, and the Prime Minister surprised not only his opposition with the knowledge obtained when the people of ZL were still asleep — even the usually alert press was now guessing.

But a few days later Bill received a letter from the Marconi Company saying: *"Dear Sir, it has come to our knowledge that you have used amateur radio to communicate with New Zealand in a way contrary to the regulation on amateur radio, and the communication used is a monopoly of the Marconi Company. We must insist that you will refrain in the future from this activity, which would result in serious consequences.*

We understand that you are studying for your PhD in radio communication at London University. We would like to assist you in your work. Please contact Mr ......, who will give you radio components — you can select — which you would find hard to obtain otherwise.

Yours faithfully"

The spirit of the Number 1 radio amateur "Marconi" was still alive!

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Propagation of Long Radio Waves

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(Continued from June issue)

Part 2. High Frequency Propagation in Brief...

In this section it is proposed to point out some main, and some possibly less known, features of high-frequency propagation, and then show how this differs from low-frequency propagation. Many characteristics of high frequency propagation are well known, and will be only referred to here.

Surface Wave Propagation

At high frequencies, the processes resulting in surface wave propagation are usually of little importance. Quite often sky wave signals and general band noise are sufficient to drown out surface waves beyond a few kilometres. Also, antennas on HF are not usually designed to optimise surface wave conditions.

Ionospheric Reflection at HF

Propagation of high-frequency waves much beyond the horizon and to great distances, depends upon reflection between the earth and the ionosphere. The process of reflection is caused by a decreasing "effective" refractive index of the ionised media with height. Reflection takes place when the wave reaches a point where the refractive index is sufficient to cause total internal reflection. In other words, the wave is refracted to a point where it is turned and returned to earth, see figure 3. (Note that in all propagation diagrams for clarity the height scale is four times that of the distance).

The ionosphere starts at roughly 70km above the earth's surface in the day an 90km at night, and increases in intensity and height to about 300 and 400km. Above this, ionisation decreases with height and is, therefore, of no consequence. The ionosphere is layered. The existence of the D, E and F layers is well known. The layers are diffuse with ionisation in between. In fact, it is probably rare to have a decrease in ionisation between the layers.

As far as high frequencies are concerned, most significant reflection takes place in the F layer, with some reflection taking place in the E layer during the day. On HF, and particularly for DX, E layer reflection is more of a nuisance than an advantage. For more information the reader is referred to the many articles on the subject of HF ionospheric propagation, some of which have been published quite recently. A very useful article, "Why is there a Maximum MUF" (Ref 1) appeared several years ago, and presents a very good basic view of HF ionospheric propagation.

Air has a refractive index slightly higher than 1, the refractive index of a vacuum equals 1. If normal physical variations were to take place in air, only very small differences in refractive index can exist and, therefore, reflection can take place only at a low angle to any layer of discontinuity in refractive index. The ionosphere can reflect at a high angle to the plane of reflection and even at right angles to the plane. Since a medium cannot normally have a refractive index less than 1, it is, therefore, obvious that the behaviour of the ionosphere is quite different from that of a normal medium.

From formula 2, if $n_1=1$ (approx for air) and i is a small angle, then total internal reflection can take place only if n_2 is less than 1. See formula 3:

$$\sin r = \frac{\sin i}{n_2} \qquad (3)$$

also, if i approaches 0^0, that is, reflection at right angles to the plane, then n_2 must approach 0^0.

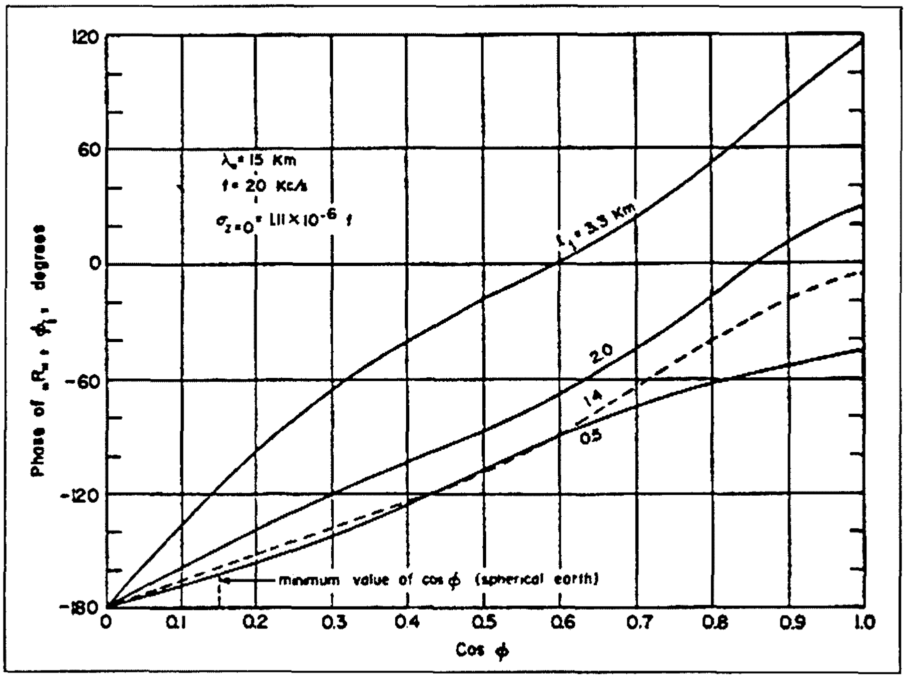
The effective refractive index n of an ionised medium is given by:

$$n = \sqrt{1\text{-}81N/f^2} \qquad (4)$$

where N is in electrons per cubic metre and f is in Hertz, N is usually in the order of 1×10^{11} to 7×10^{12}. It is obvious from this formula that n can have a value less than 1 or less than 0 (unreal). If a wave is projected vertically into the ionosphere and is turned around by the process of refraction, then not only must the refractive index be less than 1, it must equal 0. Substituting $n=0$ into the above formula we come up with the often quoted formula:

$$N\text{max}=fc^2/81 \qquad (5)$$

where fc is critical frequency and the formula tells us the ionisation density necessary to return a vertically projected signal to earth. Thus a vertical signal of a given frequency will pass into the ionosphere to a point where the electron density equals Nmax from where it will be returned to the earth's surface. If the



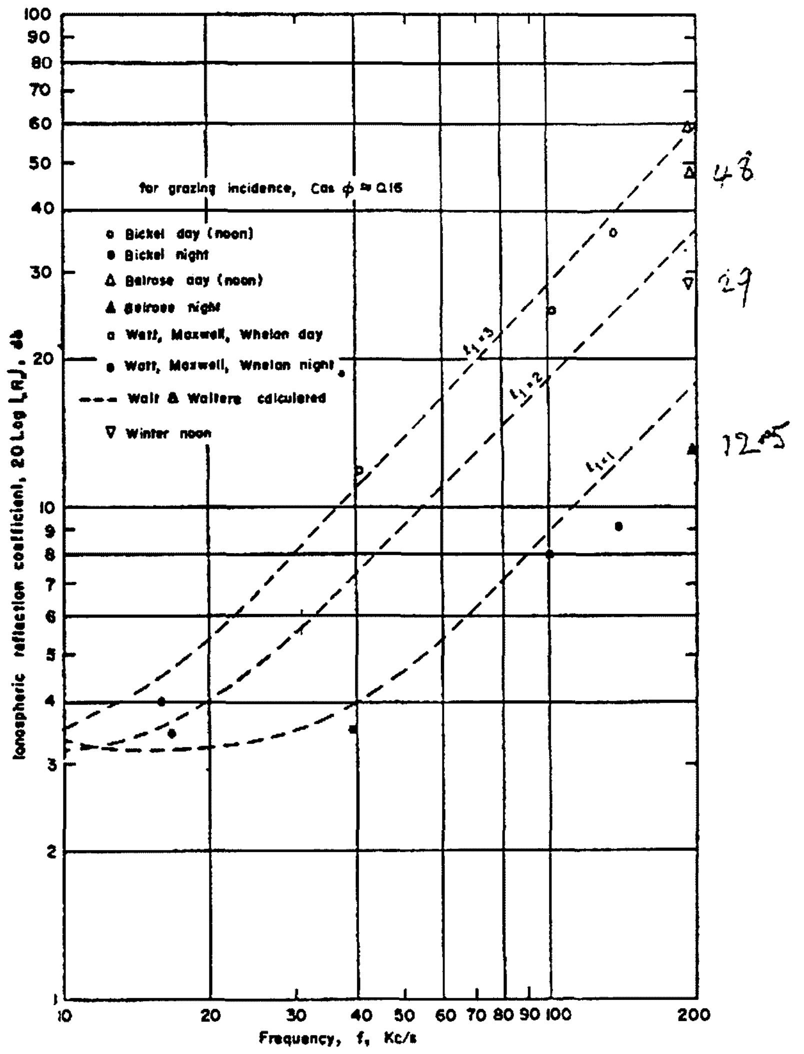
Phase of the ionosphere reflection coefficient as a function of the angle of incidence for various conductivity gradients.

angle of incidence is greater than 0° or the take-off angle is less than 90° to the ground, less ionisation is required to return the signal (see ref 1 and 2). For an angle of incidence greater than 0:

$$N=(f \cos i)^2/81 \qquad (6)$$

As referred to above, we know that refractive indices cannot normally be less than 1 or the wave propagation would be faster than light (or even faster than infinity)! When a radio signal passes through the ionosphere the electrons are caused to oscillate and, since they have mass, some energy is used in overcoming inertia. If there are no collisions between electrons and atoms there is no energy lost, and the energy in the oscillating electrons is returned to the system in the form of radiation in a different phase from the original. The process of taking energy and returning it to the system is known as *reactive* and is directly analogous to a capacitor or inductor in an electric circuit in which lossless current is drawn by the component. As referred to above, refractive index is directly related to permittivity. The ionosphere with its low refractive index also has a permittivity less than 1, and can be looked upon as analogous to capacitors in the sky! Energy being absorbed and re-radiated in this reactive medium is the effect that results in the wave being reflected or refracted.

So this behaviour of electrons in the ionosphere causes it to behave like a medium with a refractive index less than 1. What about waves travelling faster than light? We all know this is impossible. What actually happens is that the wave has two velocity components, phase velocity vp and group velocity vg (ref 2). This is a characteristic of propagation in a medium where the velocity is a function of frequency. With the phase velocity, the carrier waveform appears to move forward in time. At the same time, because of the reduced group velocity, the modulation on the wave appears to slow down. We, therefore, have a rather negative kind of refraction and reflection of HF radio waves in the ionosphere. While the wave appears to speed up as it is bent round and returned to earth, it actually slows down. The interested reader is referred to the many texts on this subject, including the reference above.



A comparison of observed and calculated ionospheric reflection coefficients vs frequency for near grazing angles

Ionospheric Absorption at HF

At the lower edge of the ionosphere there is a rather mysterious region we call the D region. The D region lies between 70 and 90km above the earth; it has no critical or maximum usable frequency but causes loss to signals passing through it at HF. Loss in the layer is large in daylight and practically negligible at night. Its loss increases with decreasing frequency and is high enough to form an almost complete blanket to sky-wave propagation below 2MHz in the daytime. This layer prevents long-distance communications over daylight paths on 7MHz and, to some extent, on 14MHz.

The D region is of great importance in LF propagation and will therefore be dealt with in more detail in the next section.

(to be continued)

References

1. "Why is There a Maximum MUF. Amateur Radio Action, Vol 6, No 6, 11 Oct '83
2. Transmission and Propagation Services Text Book, Vol 5, 1958, H M Stationery Office, 1958Appendix 14.3 and Chapter 14. Also many other similar texts.

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Errata

Sweep Generator Circuit, Page 9 *AR* April 1991

Some anomalies have been brought to my attention in the connections to N3, the MC1496 balanced mixer. The output pins omitted should be 6 and 9. Also, resistor R18 should connect to pin 5, not pin 6. The pin connections shown are for the TO5 metal package and will be different for the plastic DIL package. The other packages, N1 and N2, are both DIL.

Lloyd Butler VK5BR ar

Propagation of Long Radio Waves (3)

THE MAIN STORY

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(CONTINUED FROM JULY ISSUE)

Introduction

AT LAST WE COME TO THE purpose of the article. Most of the information in this section came from a book, *"VLF Radio Engineering"* by A D Watt who, in turn, obtained information from many publications by J R Wait. Some information was obtained from *"Ionospheric Radio Propagation"* by K Davis, and a small amount of information from practical experience by the author.

Much of the information given by Watt is literally intended to cover VLF, that is 10 to 30kHz. A certain amount of extrapolation is required to extend the range to the "higher" low frequencies. The methods given in Watt for path loss calculations are based on theory from a knowledge of the physical nature of the propagation paths and processes. Davis gives largely empirical results to calculate path loss, and these seem to depart from those of Watt in some respects. This will be discussed later in the article. It would appear that the general theory of low frequency given by Watt can be applied to frequencies up to 200kHz.

In reading this section, put most of what you know about the ionosphere out of your mind. You will find that low-frequency propagation is quite different.

Before going too far, it should be pointed out that all low-frequency transmissions are vertically polarised only. In fact, it is almost impossible to radiate any horizontal component unless you are transmitting from an aeroplane. Radiation of vertical polarisation was referred to in an earlier article (Ref 3). Some horizontal component can exist in the received signal, and this will be discussed later.

Because the experimental licence issued to several people in Australia was for operation on 196kHz (Ref 3) most of the calculations will centre around this frequency.

Surface Wave Propagation

By now most readers should be fairly familiar with this. At LF, ground loss is very low, and at all low frequencies, propagation can be of significance over distances of up to 500 to 1000km even over poor ground. Although surface wave propagation is dependent on the fairly basic physical phenomenon of diffraction described in section 1, the calculation of path loss depends upon a number of factors. In the words of texts on the subjects, it is easier to calculate path loss from graphs given for the purpose. Graphs for calculating surface wave loss are given in most texts on propagation. For the purpose of discussion, path loss graphs are given here for 200kHz and 1.8MHz (see figure 4).

At all radio frequencies, the surface wave is composed of several components. The most significant waves are direct, reflected and a wave derived from the edge of the wave shadow as described above under diffraction. At LF, the direct and reflected wave (Ref 4) at low angle to the ground are phase inverted, resulting in total cancellation. This leaves only the diffracted wave as the dominant wave. The effect of this is that, as energy is lost from the wave at ground level, wave paths above the loss area tend to bend down to fill in the gap. This bending also affects sky wave propagation, and this will be referred to again in the next section. These characteristics are shown in the general LF propagation diagram figure 5 and in an exaggerated form in figure 6.

Close to the transmitter energy is lost from the surface wave mainly due to induced currents in the lossy ground. Further from the transmitter, in the earth shadow zone, energy is lost as signal energy is fed into the gap. See figure 6. At low frequencies ground losses are low and become lower with decreasing frequency. Also at low frequencies the waves themselves are bigger. This is purely a matter of scale; big waves fill up big gaps better than small waves.

On the practical side, it is obvious from the curves (figure 4) that at 196kHz surface wave propagation is excellent, especially over seawater. For comparison, surface wave propagation is shown for 1.8MHz. This propagation is so good and completely reliable that this factor alone makes LF operation desirable. From the graph it can be seen that a 196kHz surface wave over poor ground can travel up to five times as far as a 1.8MHz wave under the same conditions. When reading this propagation graph please keep in mind that the distance scale is logarithmic.

Ionospheric Propagation

This section will deal with this subject in several basic sections, and at the end it is possible to estimate any path loss as shown in the worked examples.

The Structure of the Ionosphere as Seen at LF

Firstly we will look at the ionosphere

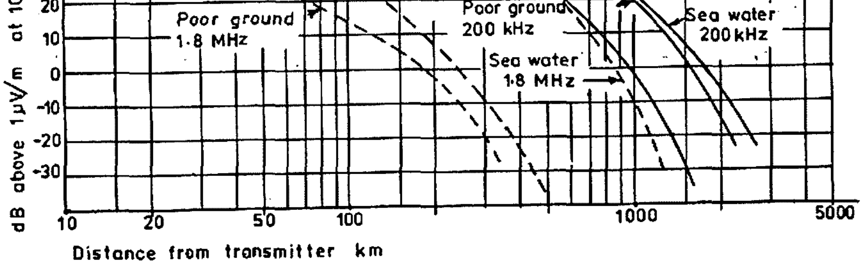

Figure 4. Surface wave propagation, 1.8MHz and 200kHz

without the earth's magnetic field. The upper ionosphere consists mainly of electrons and ionised particles. The atmosphere consists mainly of molecules with few free electrons. Loss in the ionosphere is a function of collision frequency between electrons and molecules. Where the atmosphere and ionosphere meet, a layer is formed which has a high electron collision frequency and, therefore, high loss. This lossy layer, referred to as the conducting layer, contrary to popular belief, is always present. In the daytime it is thick and exists at about 70km above the earth. At night the ionisation in the lower ionosphere is much less and the conducting layer is much thinner and exists at about 90km.

The lossy or conductive layer is like a resistive film across the bottom of the ionosphere. It exists in the region we call the D layer. The D layer can exist as a layer of ionisation but, more usually, it is simply the bottom of the E layer.

At high frequency, the D region is lossy in the daytime and basically prevents long-distance communications below about 10MHz. At night the lossy layer has little effect on high-frequency propagation, at least above 6MHz. Electrons in the ionosphere oscillate as an electromagnetic wave passes through. At low frequencies, electrons move further as each wave passes, causing more collisions. At these frequencies the whole ionosphere becomes lossy to passing waves. The loss is particularly high in the lossy or conductive layer. The D region has no maximum usable frequency in the same way as the E and F layers. The high loss renders it non-refractive and, under normal circumstances, low-frequency waves do not propagate through the ionosphere.

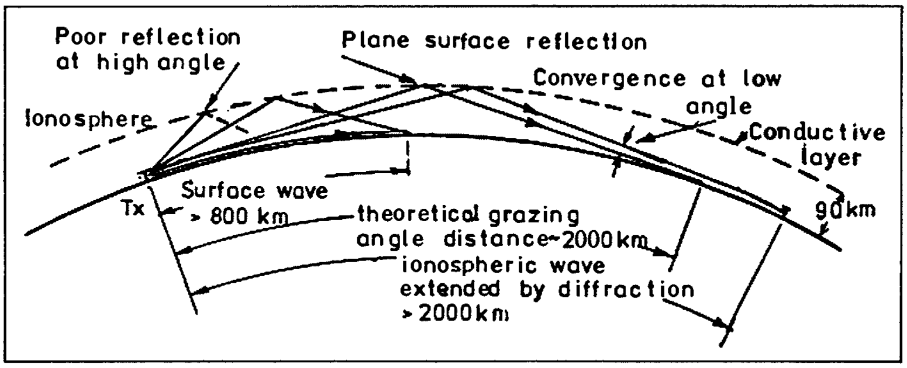

Figure 5. LF night-time propagation paths.

When electrons move through the earth's magnetic field the electrons are caused to spiral. This oscillation of the electrons of the ionosphere resonates at a frequency known as the *"gyro"* frequency. In south-eastern Australia this frequency is around 1.8MHz. The general effect is that it causes some unusual propagation near these frequencies caused by different reflections. That is, reflections at other angles than normal can be emphasised.

It is a popular misconception that loss in the ionosphere is maximum at the gyro frequency. This is not correct. The texts on the subject state that loss in the ionosphere due to the earth's magnetic field is lower than expected at HF and LF, and higher at or near the gyro frequency. This results in a knee point in the curve of loss/frequency (not shown here) of the conductive layer, but the loss certainly increases with decreasing frequency. There is a second knee or flattening off in the curve at the collision frequency of the electrons and this is around 400kHz at night.

Reflection by the Ionosphere at Low Frequency

With such a lossy ionosphere, how can any reflection take place? Actually an LF signal does not enter the ionosphere at all, but is reflected by the bottom surface. This is plane surface reflection or regular reflection as described above under "basics of propagation". It occurs at the bottom edge of the ionosphere when the conductivity increases with height significantly over a distance of a wavelength. This reflective power of the ionosphere at the bottom edge discontinuity is the same as reflection by the surface of the ground at the discontinuity between the atmosphere and ground.

To return to the optical analogy for LF, the ground and the ionosphere would both appear like sheets of glass with partly silvered surfaces. The top side of the ground and the under side of the ionosphere would poorly reflect light in our analogy perpendicular to the surface, but be quite good reflectors at a low angle to the surface.

The rate of change of conductivity with height of the ionosphere (conductivity profile) is expressed in terms of vertical distance in kilometres (*l*1) over which the conductivity changes by the ratio 2.71:1. For satisfactory reflection at LF the value of this distance, *l*1 is between 0.5 and 3.5km, depending upon the time of day and time of the year. From this value a reflection coefficient can be obtained. The reflection plane is taken as the point where the conductivity equals $1.11x10^{-10}f$ and at 196kHz this equals $2.18x10^{-5}$ Siemen/metre.

In many ways, this plane surface reflection is much simpler than the type of reflection which occurs at HF. It was known to the ancients. When radio signals were first transmitted across the Atlantic, they exclaimed that there must be a conducting layer of some sort in the sky. The conducting layer behaved exactly as expected with improving reflection coefficient with increasing wavelength. It was this knowledge which brought about the idea that wavelengths shorter than 200m were useless. A statement which amateurs never allow the professionals to forget. Realistically, it did not

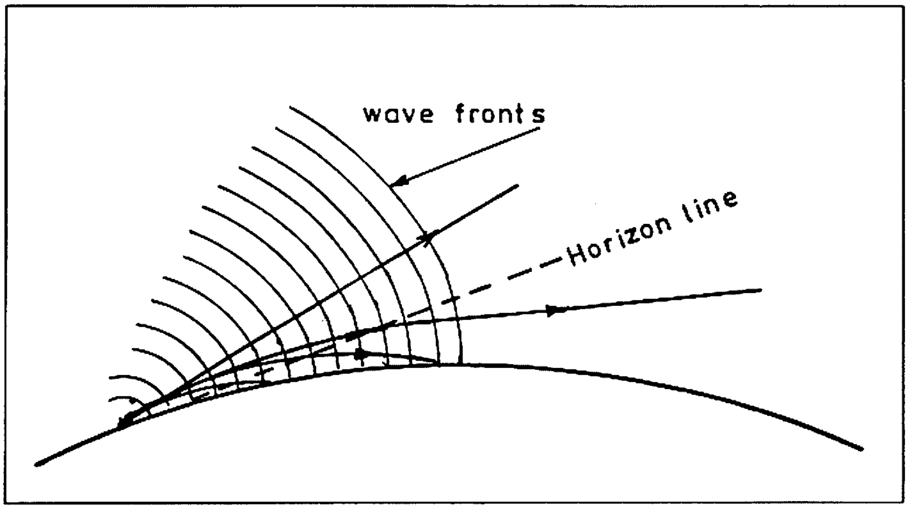

Figure 6. Exaggerated diagram showing bending of wave paths to form surface wave and bending of low angle ray to have a virtual angle below the horizon.

take them long to find out about the true nature of the ionosphere, and between 1920 and 1930 most of what we know now was discovered.

This type of ionospheric reflection which occurs at LF has a number of unique characteristics which are different from that at HF.

1. Since the reflection coefficient is dependent upon the change of conductivity over the distance of a wavelength, the longer the wavelength, or the lower the frequency, the better the reflection down to 10kHz. The reflection loss is minimum at between 10 and 30kHz. Below this frequency, the conductive layer does not have enough thickness or conductivity to maintain reflection. In other words, the first factor of conductivity profile is the limiting factor at the higher frequency end of the LF spectrum, and the second factor of actual conductivity is the limiting factor at the lower frequency end of the LF spectrum. This results in a unique form of ionospheric reflection in the LF band that is different from that in any other part of the radio spectrum.
2. Reflection by this mode is best at the lowest angle and falls off with increasing angle. This is opposite of the situation at the lower high frequencies and medium frequencies where loss is higher at lower angles.
3. Although the ionisation in this region is very low at night, the reflection coefficient is considerably improved at low frequencies, simply because the discontinuity is much sharper and occurs at an increased height. This results in a paradoxical observation that the lower the ionisation the better the reflection. At HF the opposite is true.

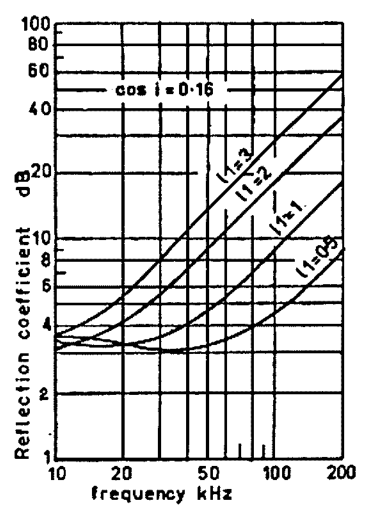

Figure 7. Reflection coefficient 20 log|R|.

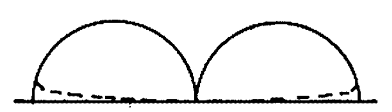

Figure 8. Simplified diagram showing cutback.

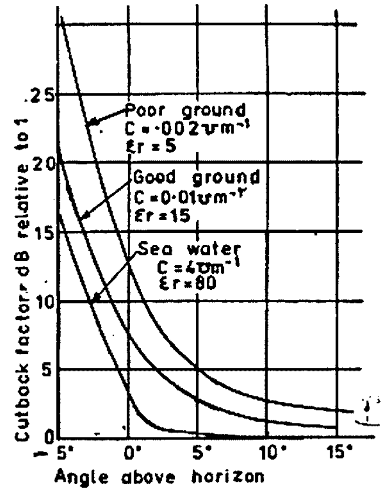

Figure 9. Cutback factor for short vertical monopole at 200kHz.

Figure 7 gives a graph of reflection coefficient expressed as loss in dB against frequency. The straight line sections of the graphs are based on the formula:

$$20 \log R = .57 f l1 \cos i \quad (7)$$

where 20log R is the reflection coefficient loss in dB, l1 is defined above, f is frequency in kilohertz, i is the angle of incidence at the ionosphere and R is the reflection coefficient for vertical to vertical polarisation. As with HF, a certain amount of the signal is converted into the opposite polarisation, but this is not detailed here. It will be noted that the log of the reflection loss in dB is simply proportional to the other factors. The vertical scale of the graph is, therefore, double log. For a particular frequency and l1, the loss in dB is proportional to cos i. The graph is correct for a cos i=0.16. This is roughly the cos of the incident angle for a grazing launching ray. For loss at other angles:

Loss dB=Loss from graph x cos i/0.16. (8)

The value of l1 is variable, depending upon time of day and year (the sunspot cycle appears to have little effect). The value of l1 is usually from .8 to 1.2 at night and from 2 to 3 at midday. In the daytime the value of l1 varies from the night-time value at dawn in a curve peaking at midday. Another significant point to keep in mind is that the height of the reflecting plane is 90km at night and drops quite rapidly to 70 to 75km with daylight. From some actual values taken from observed results at 200kHz and for cos i=0.16 given in Wait, values of 20log|R| are as follows: Night — 12.5, Winter day — 29, and summer day — 48 to 60. These correspond to values of l1 of 0.7, 1.7 and 2.6 to 3 respectively. These are the values which were used for the calculations and accompanying graphs.

Cut-Back Factor and Convergence

These two effects on the received signal strength tend to be complementary and are, therefore, both dealt with in this section.

The radiation pattern for the distant field remote from the ground from a short vertical antenna is shown by the solid lines in figure 8. Since the field strength from a short vertical antenna is proportional to the cosine of the angle to the antenna, then the field strength radiation pattern graph, when plotted on a polar diagram, will consist of semi-circles as shown. The gain of a short dipole is 1.78dBi (1.78dB relative to an isotropic) at right angles to the wire. If the antenna is above a perfect ground, the lower half of the radiated energy will be added to the upper half, and this adds another 3dB. In normal operation on long waves the antenna is always vertical and always short, and, therefore, the gain is always 4.78dBi or three times.

A simple example to clarify this is as follows. The power to an antenna is 100W and the antenna is 1 per cent efficient the equivalent radiated power at right angles to the wire is:

100x0.01x3=3W

Due to losses of the signal to the ground and to supplying the surface wave by diffraction, the lower edge of the radiation pattern is depleted as shown by the dotted line in figure 8. This depletion is well known at HF and is described in all the usual amateur texts on the subject of radiation. At HF, it usually means there is virtually no useful sky wave signal originating from an antenna, either vertical or horizontal at an angle less than 5° to the ground. This characteristic of loss of signal to the ground is known as *cutback.*

At LF, cutback is less than at HF. In fact, as a result of bending of low-angle signals due to diffraction to produce the surface wave, the sky wave path just above is also bent, resulting in radiation at a virtual angle below the horizon. This is also illustrated in figures 5 and 6. Refraction in the lower layers of air also has the effect of extending the horizon at LF in the same way as at HF.

Useful radiation can be expected for a

sky wave path when the wave path originates from the antenna at an angle of -5^0 and this is enhanced by convergence described below. This results in a considerable extension of the single hop sky wave path, and helps to compensate for the very low height of the reflecting layer. For an ionospheric reflecting layer 90km high, the expected maximum length of a single hop sky wave is about 2000km, but, with the enhancements described, the hop can be usefully extended to more than 2800km.

The graphs for cutback factor at 200kHz derived from information given in Wait are shown in figure 9.

Convergence is a focusing effect and is illustrated in figure 5. Normally signal path rays diverge, but because the reflecting surface is curved, signal path rays are caused to converge at low radiation angles. The gain resulting from convergence at 200kHz is shown in the graph in figure 10. The gain is particularly significant for signal paths just below the horizon, and significantly compensates for cutback. The gain is higher for the second and subsequent hops (not shown here).

Convergence not only takes place in the vertical plane, but also in the horizontal plane resulting from the curvature of the earth. To take the effect to its ultimate conclusion (under ideal conditions), an image of the transmitting antenna is formed at the opposite side of the earth (antipodal position) from the transmitter.

Because of much higher cutback at HF, low-angle convergence in the vertical plane would have little effect. The author has no knowledge of this effect being taken into account in HF calculations.

Reflection From the Earth's Surface After Two or More Hops

How far a low-frequency signal will travel depends very much on the power used and the frequency. At 196kHz, and with amateur power levels and antenna efficiencies, hops much beyond the first would be unusual. If a high-efficiency system is used, multi-hop signal is a possibility and, therefore, ground reflection must be taken into account.

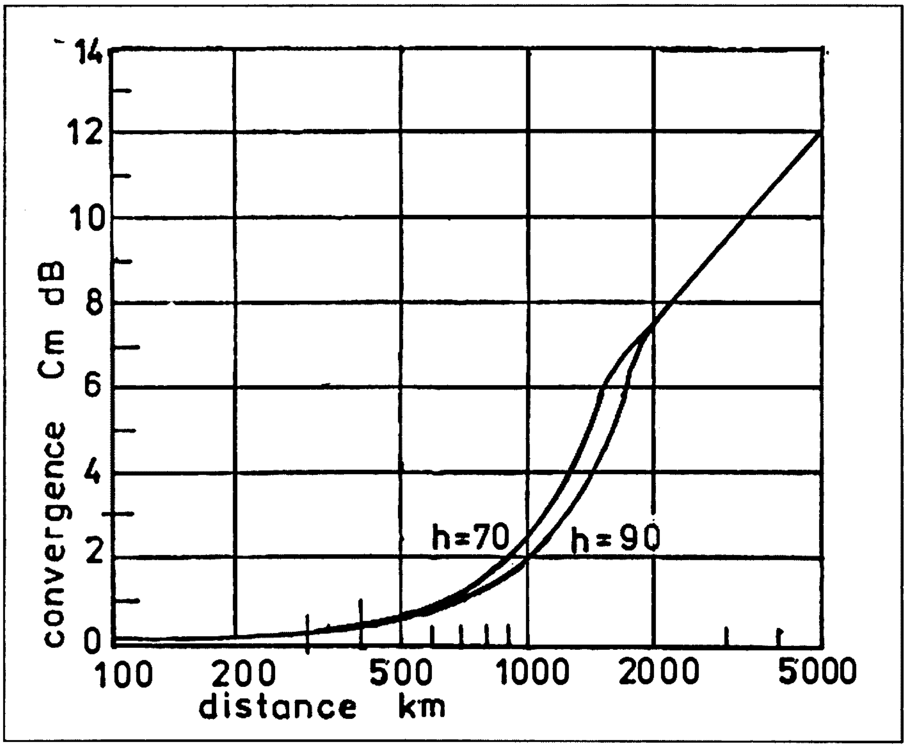

Figure 10. Convergence factor at 200kHz.

Ground loss at LF is very low. On multi-hop signals ionospheric reflection is likely to be the limiting factor. Loss for ground-reflected signals was originally described by Terman (Ref 5) and has been duplicated in almost every textbook on the subject of propagation. It is not proposed to reproduce a ground reflection loss graph here. The reader can refer to the many texts on the subject.

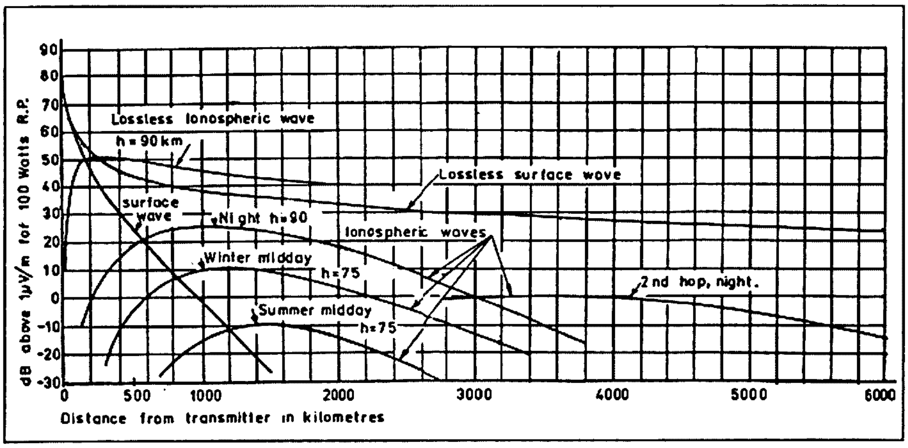

Figure 11. Propagation chart for 196kHz above poor ground

Other Factors in Sky Wave Propagation

The loss in ionospheric reflection is such that only low-angle radiation can be considered. At very low frequencies, loss in the ionosphere is low, allowing long-distance communications.

The loss in reflection from the ionosphere shown in figure 7 is not all total loss. The graph represents reflection of vertical to vertical polarisation. As with HF ionospheric reflection, a proportion of the energy is converted to horizontal polarisation. This is brought about by interaction between moving electrons in the ionosphere and the earth's magnetic field. Horizontally polarised waves are undetectable at ground level due to phase inversion and cancellation. The horizontally polarised component is reflected by the ground and on the second hop some signal is converted back to a vertically polarised signal and adding to the second reflected vertically polarised signal.

The magnitude of both the direct reflected wave (vertical to vertical) and the converted reflected wave (vertical to horizontal) is affected by the direction of the earth's magnetic field and the direction of propagation. These effects are very complicated and won't be considered here, but it is interesting to note that propagation is better in some directions, particularly from west to east.

As well as path loss, it is possible to calculate the relative phase of the signal along its path. For example, where the sky wave is similar in strength to the surface wave, or where the first hop is of similar strength to the second hop, it is possible to determine whether they add or cancel. This is also not dealt with here, to simplify calculations. It can be considered that, where two paths meet and are of similar strength, the average effect is an increase of 3dB, but complete cancellation with a zero strength is possible.

Calculation of Path Loss With Examples

The calculation of surface wave field strength is as follows:

$$\text{Ezg}[\text{dB above } 1\mu\text{V/m}]=109.5 + 10\log \text{Pr}[\text{kW}] - 20\log d[\text{km}] + 20\text{Log}|\text{Wn}| \qquad (9)$$

104.8 is the field strength in dB above 1uV/m at 1km from an isotropic antenna radiating 1kW. 109.5=104.77 plus the gain of a vertical short monopole above ground, 4.78dB. 10Log Pr[kW] is the correction for radiated power. 20Log d is the loss due to spreading over the path distance in kilometres. 20Log|Wn| is a negative value and can be obtained only from graphs published in many texts on propagation. The value of the whole equation can similarly be obtained. It is not proposed to further elaborate on equation 9.

NP calculation of sky wave field strength is as follows:

$$\begin{aligned}\text{Ezm}[\text{dB above } 1\mu\text{V/m}]=109.5 &+ 10\log \text{Pr}[\text{kW}] - 20\log(d+ d1)\,[\text{km}] + \\ &20\log(\cos et) - \text{Lt} + 20m\log|\text{Ri}| + \\ &20(m-1)\text{Log}|\text{Rg}| + \\ &\text{Cm} + 6 - \text{Lr} + 20\log(\cos er) \qquad (10)\end{aligned}$$

109.5 is defined above. 10Log Pr[kW] is also defined above. 20Log(d+d1) [km] is the loss due to spreading over the total path distance in kilometres. The path distance for a sky wave is calculated from the geometry of the configureuration. To save space, no explanation of the method is shown here, but reference 1 gives a good guide. Lt is the cutback factor at the transmitter. 20mlog|Ri| is the ionosphere reflection loss for each of m hops obtained from figure 7 and/or equations 7 & 8. For multi-hop, polarisation conversion at reflection may be appropriate, but is not detailed here. 20(m-1)log(rg) is the ground loss for each of m hops. Ground reflection is included in most texts on propagation, and is also not detailed here. Cm is convergence factor (see figure 10).

20log(cos et) and 20log(cos er) represent the vertically polarised component of the signal at a radiation angle e at both the transmitter and receiver. (In other words, radiation pattern). Normally the radiation angle at the transmitter is the same as the reception angle).

6dB shown here represents the amount the vertically polarised signal strength above a perfect ground is increased at the receiver, because of the adding of the direct ray and the ray reflected from the ground. Lr is the cutback factor, which modifies the signal at the receiver in the same way as at the transmitter. It represents the amount by which the received signal is reduced by ground loss. In Watt, the 6dB gain of the antenna above a ground is included in the cutback factor graphs, but the author believes the method used here is more straightforward.

Using these formulas, graphs for path field strength have been worked out for propagation at 196kHz. On the graphs, the line for a lossless surface wave and a lossless sky wave are shown. The graphs have been worked out for a transmitted power of 100W. In practical situations, the radiated power is a lot less than this, and in a back-yard situation may be less than one per cent. The reader should, therefore, correct the field strength shown according to the actual power. The path signal strengths are shown in figure 11 with a linear distance scale for clarity. All graphs have been worked out for a poor ground with a relative permittivity of 5 and conductivity of .002 Siemen/metre.

Readers might find all this a little hard to follow. The only way to understand it properly is to set a problem and work it through. The author has placed the calculations on computer, but at the moment the procedure is not complete.

A sample calculation sky wave propagation is as follows:

Frequency	196kHz
Earth radius	6370km
Atmosphere factor	1.33
Hops	One
Earth	Poor
Time of day	Night
Radiated power	100W
Assume loss for cos i=0.16 is 12.5	
Distance	1000km
Ionosphere height	90km

First factor	109.5
10log Pr[kW]	-10.0
Path distance	(1021)
-20log(d-d1) [km] spreading	-60.1
Elevation angle radiation Et	(8.40)
cos Et (antenna pattern)	(0.99)
20log(cos Et)	-0.1
-Lt cutback	-3.3
Incident angle at ionosphere	(78.10)
Cos i	(0.20)
20mlog(Ri) at i=77.6	-16.0
Cm convergence	2.0
+6	6
-Lr same as Lt	-3.3
20log(cos Er) reception angle (same as for Et)	-0.1

Total signal strength at 24.4dB above 1uV/m receiver

Atmospheric Noise

The final factor to be considered is atmospheric noise. No matter how strong a signal is, signal to noise ratio is always the limiting factor. Of course, man-made noise is also important, but it is quite unpredictable. Atmospheric noise at LF is high and increases at a very high rate with decreasing frequency. Noise maps and curves are given in texts on the subject. Several typical noise figureures are given here as a guide to noise level on 196kHz. They are based on noise maps at 10kHz. Doubt is expressed as to whether the figureures can be extrapolated this far, but they may be useful. The figures are based on CW reception with 100Hz bandwidth at 200kHz reception frequency and are relative to 1uV/metre.

Summer day	-15dB
Summer night	-5dB
Winter day	-30dB
Winter night	-18dB

Final Observations

Low-frequency propagation (10 to 200kHz) differs from high-frequency propagation in a number of respects. Surface wave propagation is very strong. There is no skip zone, even though only low-angle sky wave radiation is dominant. This is because of the low height of the reflecting plane, and the long distance travelled by the surface wave. Where the surface wave meets the sky wave, the two merge together, possibly with some cancelling or adding of the two where the strengths are equal. From observation at the receiving site there is no apparent difference between a surface wave and a sky wave. The only actual difference is that the phase velocities are different. More will be said about this in section 4.

From 200kHz down, both surface wave and sky wave improve. The result is that the zone where the surface wave equals the sky wave remains between 500 and 1000km. At 200kHz propagation is poor in the day and reasonable at night. Between 10 and 30kHz, propagation is excellent both day and night. The main limiting factor from an amateur point of view is noise level. The frequencies where propagation is best are those where noise is highest. This is the main reason for very high powers being used for very long distance communications. Another reason for high powers being used is poor antenna efficiency.

On the frequency used by the small group of experimenters here (ref 4) signals transmitted by the author were heard day and night in Adelaide and Hobart, and at night in Brisbane. I don't think the full potential of this has been realised. Experimenters in America with very small power have achieved quite good results.

References

3. Experimental Stations on 196kHz, *Amateur Radio*, July 1984
4. Good explanations of surface wave propagation appear in the RSGB *Amateur Radio Handbook*, and moat textbooks on propagation
5. *Radio Engineers Handbook*, Terman, Section 10, Article 5, Reflection of Radio Waves

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Propagation of Long Radio Waves

PART 4 CONCLUSION

(CONTINUED FROM AUGUST ISSUE)

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Horizontal Polarisation

IN THE PRECEDING TEXT IT WAS stated that with an LF signal there is no horizontal polarisation present perpendicular to the direction of propagation. There is, however, horizontal polarisation present in the direction of propagation. I wish to discuss several aspects of both these statements.

Horizontal Polarisation in the Direction of Propagation

When a vertically polarised signal travels over the surface of the ground the lower end of the wave front, in effect, drags behind the space wave above the ground (see figure 12). This is brought about by the ground having a higher conductivity and refractive index than the air, and causing the wave to have a lower phase velocity in the ground than in the air (or space). In fact, this is an application of the optical law which states that when a wave moves from a medium of low-refractive index to one of higher refractive index, the direction of propagation of the wave will bend towards the normal, that is it bends towards the perpendicular to the ground. In fact, below the ground the signal is almost horizontally polarised.

The effect of this is that, at a relatively low height above the ground a horizontally polarised component of the signal exists. This component is present in both the surface wave and the normally vertically polarised component of the sky wave and, surprisingly, the effect can be of significance at HF. The phenomenon allows the use of a directional receiving antenna known as the *Beverage* (see Figure 12). The Beverage antenna is basically a long wire travelling wave antenna running in the direction of the received signal. The antenna is usually terminated in a resistor equal to its characteristic impedance at the front end and the receiver at the far end. The antenna can be less than a wavelength to many wavelengths long; the longer the better.

The principle of the antenna is that it intercepts the horizontal component of the signal as it travels along the antenna. The induced signal adds in the antenna until it reaches the receiver. These antennas have been traditionally used on long wave since early times. Most amateurs may not be able to erect such an antenna long enough to be of much use on LF. The method is still worth keeping in mind. Many amateurs have certainly used Beverage antenna on 1.8MHz and higher with considerable advantage.

Horizontal Polarisation Transverse to the Direction of Propagation

It was stated above that this characteristic is ineffective at ground level. Horizontal polarisation reception at the higher medium frequencies has been of particular interest to the author, and was the main subject of an article some years ago (Ref 6). Many amateurs have made use of short or full-size dipoles on 1.8MHz for reception with great advantage, and it is felt that a more detailed discussion is in order.

Refer to figure 13. Imagine the transmitting antenna is at point 'a' and the receiving antenna at point 'b' shown as a horizontal dipole. An electromagnetic wave is a transverse wave motion and can, therefore, only be polarised perpendicular to the direction of travel of the wave. If the propagation is along the ground, direction A, that is, perpendicular to the antenna (assume a lossless situation), the strength of the signal at a given distance will depend upon the radiated power and distance. If the direction of radiation is vertical, direction C, there can be no radiation as an antenna cannot radiate off its end. If we consider a direction of propagation at an angle, direction B, to the ground then, from the geometry of the configuration, the field will have an amplitude proportional to the cosine of the angle to the ground. This is shown by the vector triangle in figure 13. In the case shown, the angle of radiation 'e' is at 60^0 and, therefore, the strength of this field is reduced by cos 60, that is, 0.5 or -6dB.

This cosine factor is the cosine in equation 10. In similar manner, when the signal reaches the receiver, assume a vertical antenna here for the moment, the polarisation is not parallel with it which, by the same geometry, is also proportional to the cosine of the angle to the ground. This is the second cosine function in equation 10.

If the receiving antenna is a horizontal dipole, then reception is maximum vertically and zero horizontally. Even though the transmitting antenna is vertical, the received signal has a horizontal component parallel to the ground, so long as the launching angle is not completely vertical or horizontal. The received component of the incoming signal parallel to the antenna is proportional to the sine of the angle of reception to the ground. In the case under discussion for a reception angle of 60 to the ground, the received signal will be reduced by sin 60, that is, .87 or 1.2dB. This is shown in the second vector diagram in figure 13.

On medium frequency a dipole, even a small dipole, which is balanced and accurately horizontal will give high rejec-

Tower Height Adjuster

Continued from page 15

antenna parts, leaving the motor and clutch. See figs 1 and 2. I fitted the motor to a 3mm plate with bolts, and fitted a nylon 30mm gear from a washing machine to the clutch with little bolts. The clutch was a plastic cone with a centre tensioning bolt. Another gear of 100mm diameter was mounted on a spindle attached to the motor plate with a spool for the wire to raise and lower the tower section.

The motor assembly was mounted under a carport near the tower. An up/down switch and a 12V supply allow the tower section to be raised and lowered from the operating position. To indicate the position of the tower section I fitted a potentiometer with a long arm to the raising and lowering wire. An old meter obtained from an SWR meter was used to indicate the position. The potentiometer varies the current from the 12V supply, and the meter can be calibrated with the tower position. See figs 3, 4, 5, 6 and 7. **ar**

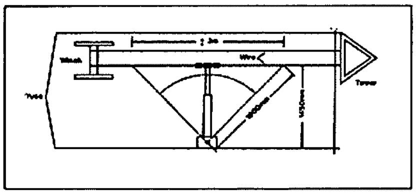

Figure 6. Connection of Arm to Pot.

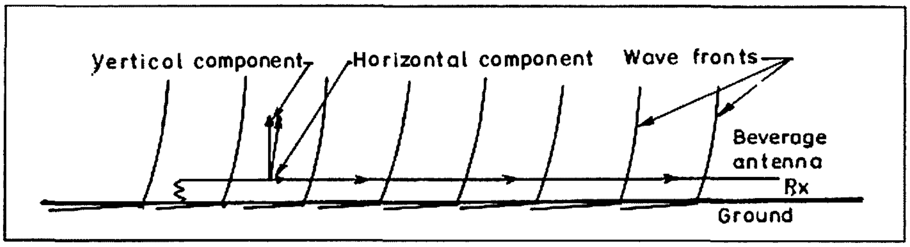

Fig 12 Showing how a travelling wave is formed on a Beverage antenna.

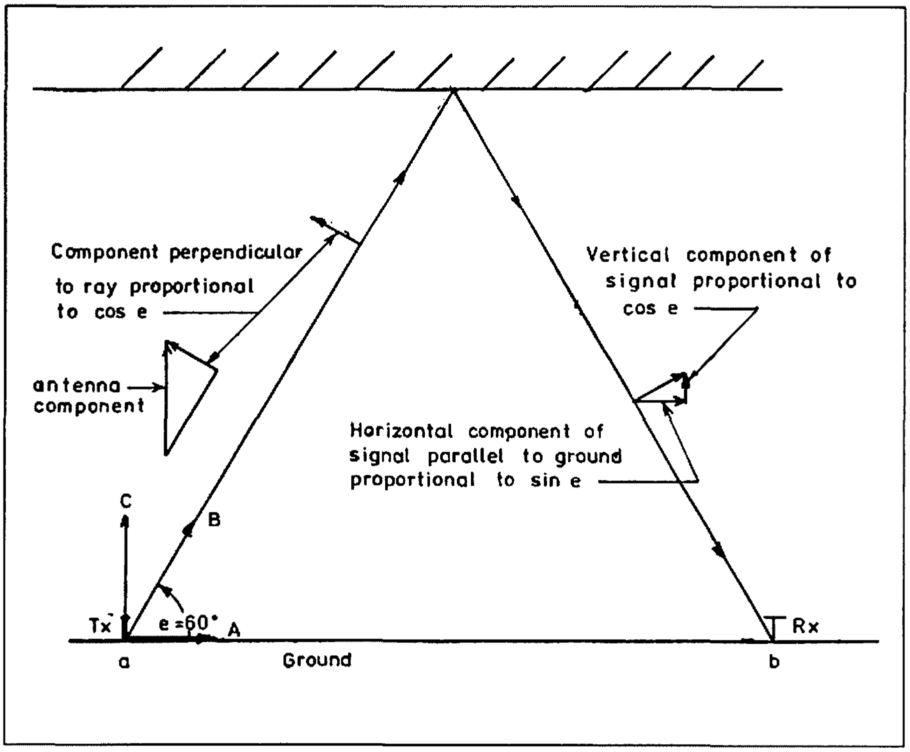

Fig 13 Showing that a signal ray with a high angle of elevation has a strong horizontally polarised component even when transmitting antenna is vertical.

tion against vertical polarisation. Such an antenna will reject the surface wave and most noise and enhance the high-angle wave. On 160m horizontal polarised reception is a great advantage in the "interference zone" where the surface wave equals the ionospheric wave and beyond up to about 800km.

(Surprisingly horizontally polarised reception on 160m not only gives better reception on short hop signals, but often gives better results for DX reception. The reason for this is not easily explained and could be a subject for research).

On low frequency, one might expect to obtain a similar advantage. However, such is not the case, and this leads to the next subject.

Lack of High Angle Radiation on Low Frequency

The lack of high-angle radiation on LF is not surprising when you look at equation 7 and also observe Figure 11. From equation 8, it is obvious that at frequencies much above 200kHz the reflection coefficient at the conductivity discontinuity will be poor at low angles. At this rate there would be no ionospheric propagation of the type described here in the broadcast band at all.

There must be a transition between reflection at the conductivity discontinuity described in Part 3 of this article, and reflection due to decreasing effective refractive index with height described in Part 2. What might happen is that, at a high angle of radiation — say at 200kHz — the reflection at the discontinuity is very poor. Some of the signal might pass through and be reflected by the E layer in the manner described in Part 2 (HF type reflection). This change should become more obvious with increasing frequency, and probably the transition takes place somewhere in the broadcast band. Texts on this subject are very poor in information on ionospheric propagation on medium frequencies.

If a high-angle signal exists it should be detectable with a dipole. Also, if a dual path exists, this should also be detectable in the form of very slow fading under certain conditions. The author has tried a number of experiments at his QTH to detect high-angle radiation using a dipole. Non-directional beacons at the LF end of the beacon band were used as experimental signals. So far, no high angle of radiation has been detectable. This would tend to indicate that the method of calculating ionospheric reflection coefficient given by Watt is correct, at least below 250kHz.

The main difficulty with this experiment is that a low short horizontal dipole is very inefficient. This is firstly because it is short and secondly because of interaction with the ground at a low height. The efficiency of a low short dipole decreases approximately with the fourth power of the inverse frequency. For example, if a dipole delivers 100 microvolts to a receiver at 1.8MHz for the same signal strength it will deliver 1 microvolt at 196kHz. A second difficulty with the experiment is that the surface wave is very strong and a high vertical rejection is required by the dipole.

This low output is not impossible to work with. If there was any high-angle signal content in the received signal, it should be detectable. The experiment is certainly worth repeating with a bigger dipole. There must be plenty of people living in the country with big dipoles.

The Sporadic E Similarity

It was stated in part 3 that this plane surface type reflection was unique to LF. However, one can't help observing the similarity between this type of reflection and reflection by sporadic E at HF/VHF. Reflection by sporadic E was described recently in an excellent article in 'AR' (Ref 7). Sporadic E is similar, in that it is in the form of a thin mirror-like layer, the reflection coefficient is less the higher the frequency, and it is better at a low angle than at a high angle. It is also noted that a high-angle signal is only partly reflected and part is reflected by the layer above.

Surprisingly, there is such a thing as "sporadic D"! Usually referred to in LF as ionospheric disturbances. Stratified ionised layers can form between 50 and 90km above the ground, and are described by Watt. Although they do not reflect HF, and may result in increased loss, at LF they result in signals being reflected at a lower height.

VLF Ducting

Wave guide type ducting between the

D layer and ground for LF waves between 10 and 30kHz is fairly well known, and often referred to in articles on the subject. Although this frequency range falls outside that covered in this article, it is interesting to show how ducting relates to all that we have been talking about. Some explanation is in order.

There is no space available to explain wave guide theory here, and interested readers should refer to the many texts on the subject. Even at 10kHz, the gap between the ionosphere and ground is more than a wavelength. Briefly, when an electromagnetic wave is ducted in a wave guide with surfaces more than a wavelength apart, waves will travel along the guide, being reflected between the two surfaces at such an angle that the wave fronts are all in phase vertically. That is, in the case of the VLF propagation, each wave front advances as a single unit spanning vertically from the ground to the ionosphere. The angle of reflection of the waves forming the waveguide mode is critical. The most basic mode is the TEM1 mode. The TEM2 mode is a second-order resonance etc. The angle of the rays to the surface forming the mode decreases with increasing frequency.

Propagation efficiency for a particular mode between the ground and ionosphere is low, when the angle of the ray to the ground is high, and is maximum when the angle to the ground is zero. Above a certain frequency, the particular wave guide mode parts company from the ground, and exists under the ionosphere only, and thus becomes decoupled from the antenna. The TEM1 mode reaches maximum efficiency between 12 and 20kHz. The TEM2 mode reaches maximum efficiency between 20 and 40kHz, depending upon the time of day or night. Above the TEM3 mode, the modes become so mixed they are of little significance.

The phase velocity of propagation making use of these modes is very accurately predictable, and it is on this principle that the Omega navigation system operates.

In brief, propagation at 200kHz is the same as at 10kHz, in that it depends on reflection between two low-conductivity concentric spherical surfaces between 70 and 90km apart — the ground and the conducting or D region of the ionosphere. One difference is that, at the low-frequency end of the band, the propagation is dominated by wave guide modes which control the wave front velocity, and in general make propagation very predictable over global distances. With increasing frequency, propagation efficiency falls off, until other propagation media become dominant. At frequencies below 10kHz, the high angle of reflection determined by the TEM1 mode as well as insufficient conductivity in the D region causes propagation efficiency to fall off.

Final

With all this I will go back into my shack for a while and leave readers to think about it. After a while, I would like to hear some interesting discussion on the subject.

References

6. Home Station Antenna for 160 Metres, Amateur Radio, May to December 1971
7. Sporadic E Propagation at VHF, Peter Stackpole VK1RX, *Amateur Radio* June 1989.

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Remember to leave a three-second break between overs when using a repeater