densely ionised region must be present in the upper atmosphere, and in consequence this region is generally known as the **Kennelly-Heaviside Layer.** The word "layer," however, is rather misleading, since the region has no sharp boundaries.

The ionisation in this region is mainly due to the presence of free electrons. Its cause is still obscure, but the main factor appears to be the ultra-violet radiation from the sun. Such radiation is most potent at the outer edge of the atmosphere, but the actual number of free electrons it produces also depends, of course, on the number of molecules which are present to be ionised. This number increases as the height above the earth decreases, but the ultra-violet radiation is also being absorbed as it penetrates the atmosphere. The result is that the maximum density of free electrons is produced in some region intermediate between that in which electrons are first liberated and the surface of the earth. The least height at which the ionisation exercises an appreciable effect on the direction of propagation of wireless waves is about 60 miles. This lower limit is by no means sharply defined. It varies considerably from winter to summer and between night and day.

After sunset the ultra-violet radiation ceases to be operative, and in the lower regions where the density of the atmosphere is greater, and collisions between electrons and molecules are more frequent, there is a certain amount of re-combination between electrons and positive ions. The ionisation in these regions therefore decreases between sunset and sunrise, and the effective lower limit of the Heaviside Layer moves upwards, rising slowly through a distance of about twelve miles during the dark hours, reaching a maximum height before sunrise and falling rapidly after sunrise to its daylight value.

The ionisation gradient, *i.e.*, the rate at which the density of ionisation varies with height, appears to be considerably greater from the region of maximum ionisation to the lower limit of the Heaviside Layer than it is above the region of maximum ionisation.

733. Reflection and Refraction in the Heaviside Layer.—The dielectric constant of the atmosphere is altered by its ionisation, the effect being to make K less than unity. Thus wireless waves travel faster in the layer than they do in the free æther. A distinction must, however, be made between the rate at which a signal (consisting of wave trains) travels, and the speed of the individual waves composing it. This may best be realised by considering the effect of dropping a stone into a pond. A disturbance in the form of a wave motion travels outwards over the surface of the water from the point where the stone entered. If one individual wave is watched, it will be seen to travel through the disturbance, and appear to die out when it reaches the outer edge. There are still, however, as many waves in the disturbance as there were before, new waves appearing at the inner edge as the ones at the outer edge disappear. In other words, the individual waves are travelling faster than the wave train as a whole. The speed of the individual waves is called the **phase** velocity, and that of the train is called the **group** velocity.

In the free æther (and sensibly in the lower atmosphere) these two velocities are the same, but in the Heaviside Layer the phase velocity is greater than in the lower atmosphere, and this is what is meant by the statement that wireless waves travel faster in the Heaviside Layer. The velocity of the signal, the group velocity, is no greater and may be less in the layer than in the lower atmosphere.

It has been explained above that when electromagnetic waves pass from one medium into another in which they travel faster, as in the case of light waves travelling from water to air, they are refracted so that their direction of travel is more inclined to the normal to the common surface. When this common surface is approximately horizontal, like that of the Heaviside Layer, the result is that the wave travels in a more horizontal direction in the layer than in the atmosphere below it. The ionisation in the layer is not homogeneous, but increasing with height, and so the phase velocity of the waves also increases in a gradual manner as the wave ascends. Instead of an abrupt change of direction, therefore, the effect of the ionised region is to cause a gradual bending of the direction of the wave. This may be sufficient to bend the wave direction round until it is travelling parallel to the earth's surface, and eventually to direct it downwards so that it again returns to the earth at a distance from the transmitter. The final bending downwards may arise by gradual bending due to refraction, or by a process resembling more closely a reflection when the incident wave reaches the critical angle.

The possibility of the wave returning to earth depends mainly on two factors :—

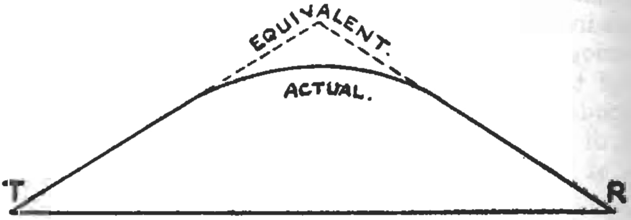
(1) The frequency of the wave.
(2) The angle at which it originally enters the layer.

For a given angle of incidence the frequency determines the actual amount of bending that takes place, since the change in phase velocity in different parts of the ionised region depends on the frequency.

The amount of bending necessary before the wave can be altered sufficiently in direction to travel downwards obviously increases the more nearly perpendicular the original wave is to the surface of the layer when it enters.

It is therefore evident that the height to which a wireless wave penetrates the layer, and the possibility of its return, depend both on the frequency of the wave and the vertical angle at which it is radiated from the transmitter. Further, waves of the same frequency, but differing in angle of incidence, if they return to earth at all, will be refracted differently and pursue different paths in the layer, and therefore will return to earth at different distances from the transmitter. The radiation from an ordinary vertical aerial is not at one particular angle, but waves are radiated to some extent at nearly all angles to the horizontal. They thus arrive at different points of the Heaviside Layer with different angles of incidence, and the waves returning to earth are spread over a large zone of the earth's surface.

For L.F. waves, the bending takes place in a depth of the Heaviside Layer comparable with the wavelength, and so is more in the nature of reflection, as it is understood for light waves, than refraction. Even in the case of H.F. waves, when the depth of penetration may be many wavelengths, it is customary for simplicity to assume the process of refraction replaced by one of reflection, in which case the height of the equivalent reflecting surface is considerably greater than the actual height to which the waves penetrate. The actual and equivalent processes are illustrated in Fig. 435.

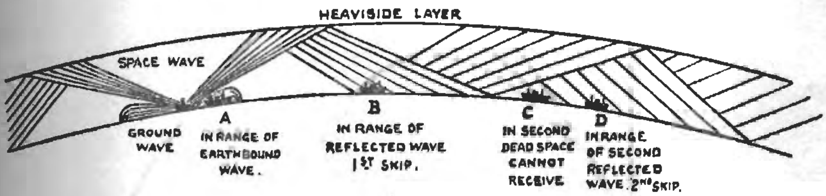


Path of Indirect Ray.

FIG. 435.

734. Skip Distance.—For any given frequency there is one direction which the ascending ray makes with the earth's surface at which it is most quickly bent round in the Heaviside Layer. The point at which this wave reaches the earth is therefore the nearest point to the transmitter at which signals can be received by means of waves returning from the upper atmosphere. The distance from the transmitter to this point (which is, of course, not a point, but a line round the transmitter on the earth's surface, and would be a circle if the radiation and the effect of the Heaviside Layer were the same on all bearings) is known as the skip distance. Within this distance the only signals that can be received are those due to the direct wave travelling along the earth's surface.

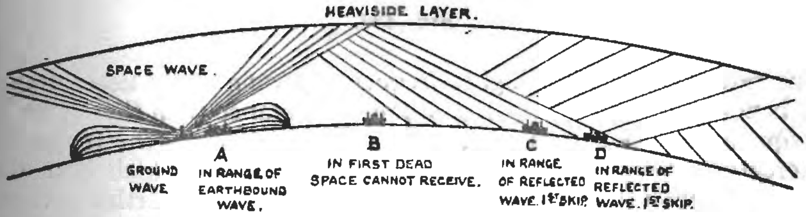
In the case of H.F. waves the range of the earth-bound ray may be considerably less than the skip distance, and so there appears a zone of silence in which no signals are received. This is shown diagrammatically in Fig. 436. The shaded parts represent the paths of the waves. The diagrams also show that the downcoming wave may be reflected at the earth's surface, travel up again to the Heaviside Layer, be bent round and return to earth still further away, giving rise to other zones of silence. This question of multiple reflection will be further treated below. The regions where no signals are received are generally called **dead spaces,** being known in order as the first dead space, second dead space, and so on. The parts of the earth's surface where signals due to the refracted radiation can be received are called zones of reception. It will be seen as a matter of simple geometry that the width of the second dead space is less than that of the first dead space, and so on, and that the width of the zones of reception increases correspondingly.



DAY

HEAVISIDE LAYER LOW.

(a)



NIGHT

HEAVISIDE LAYER HIGH.

(b)

FIG. 436.

It may appear from the diagrams that the refracted ray corresponding to the ray of steepest incident angle that returns at all, returns to earth nearest the transmitter, and so determines the skip distance, but this is not necessarily the case. Actually, rays of different angle penetrate to different heights, and therefore meet different refracting conditions. Of two rays of the same frequency, at different angles of incidence, that at the lesser angle may return to earth nearer the transmitter than the more steeply incident one.

The two diagrams of Fig. 436 also indicate the difference between day and night conditions. The effective equivalent height of the layer is higher at night, and so, for rays of the same frequency and angle of incidence, the skip distance is greater. The skip distance at night is generally three or four times as great as the day skip distance.

The higher the frequency of the transmitted wave, the less is the degree of bending it experiences in the Heaviside Layer, and so the smaller is the limiting angle of incidence at which rays will be bent round sufficiently to return to earth. This is illustrated in Fig. 437 for three waves of different frequencies radiated at the same angle to the earth. The wave of highest frequency is able at this angle to penetrate the layer completely, and does not return to earth. The returning wave of higher frequency, owing to its lesser degree of bending, returns to earth at a greater distance than that of lower frequency. The skip distance therefore increases as the frequency increases. Eventually a frequency is reached at which even the most obliquely incident ray fails to return to the earth's surface. This limiting ray probably comes out of the Heaviside Layer, as shown in Fig. 438, but in such a direction that it misses the earth's surface and returns into the layer, going on in this way until it is completely attenuated. The highest frequency at which regular long-distance transmission is possible is about 35,000 kc/s. (8·5 metres) in daylight, and the corresponding frequency at night is about 16,000 kc/s. (18·5 metres).

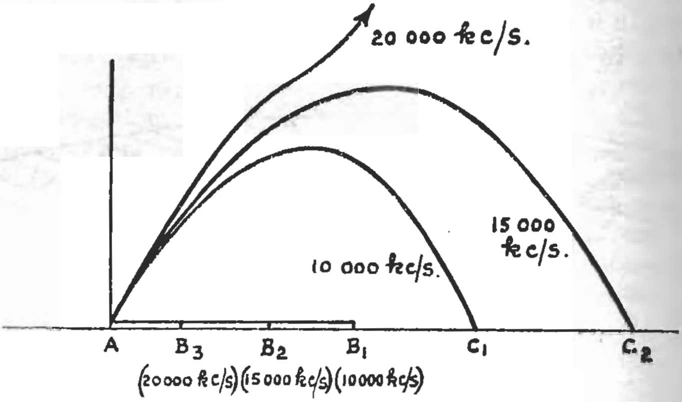


FIG. 437.

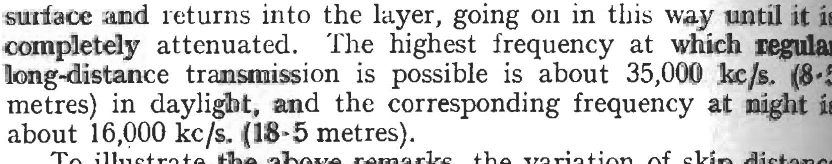
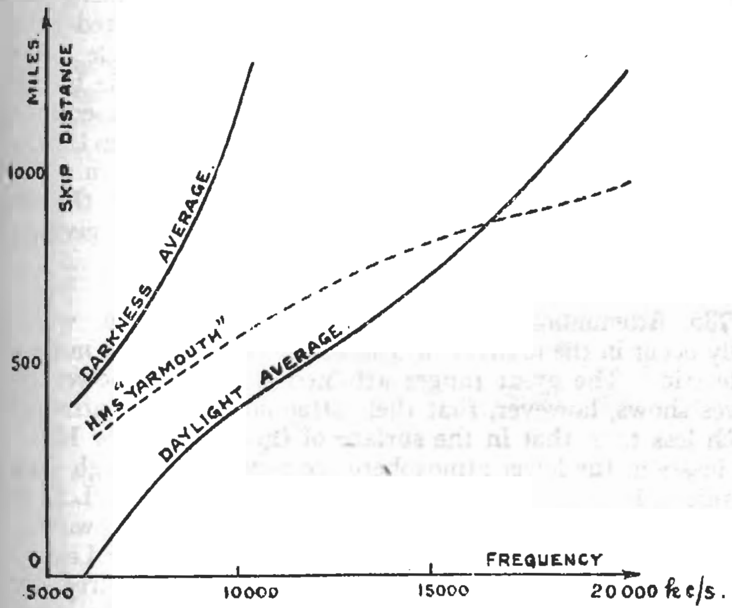


FIG. 438.

To illustrate the above remarks, the variation of skip distance with frequency at high frequencies is shown in Fig. 439, the two full lines corresponding to paths between transmitter and receiver lying altogether in daylight and darkness respectively.

The increase of skip distance with frequency and the much larger skip distances at night should be noted. The shapes and relative positions of the curves are probably fairly accurate, but the actual figures should be treated with reserve, since the experimental evidence is rather conflicting. The values given are average values over a year. In summer the skip distances are less than in winter.



Variation of Skip Distance with Frequency.

FIG. 439.

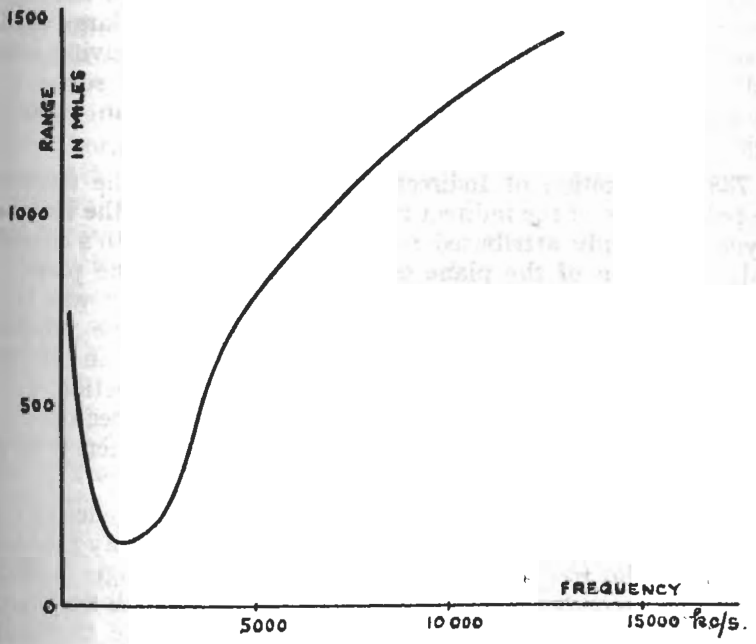
Some figures obtained in H.M.S. *Yarmouth* on a cruise to Hong Kong and back in 1925 are given in the following table, and are also shown in Fig. 439 by the dotted line.

f. (kc/s.).	Skip distance (miles).	Range of earth-bound component (miles).	Width of first dead space (miles).	Width of first zone of reception (miles).	First overlapping zones.
25,000	1,100	30	1,070	800	2nd and 3rd.
12,000	720	80	640	440	2nd and 3rd.
8,500	520	170	350	240	3rd and 4th.
6,250	350	350	Nil	60	No over-lapping up to 6,000 miles.

It is not strictly correct to say that no signals can be received in dead spaces, but the signal intensity is very weak there compared with that in the zones of reception (less than one ten-thousandth). Such signals as are obtained are attributed to " scattering " of the indirect waves in the Heaviside Layer. Instead of being gradually bent round, part of the stream of energy is scattered in various directions, and so may descend to earth at any angle. A similar phenomenon in the case of light waves is responsible for the blue colour of the sky during the day. If the earth possessed no atmosphere, the only sunlight waves reaching it would be from the direction of the sun, and the sun would appear as a bright disc in a black sky (apart from the stars). But the atmosphere scatters the sunlight, and it appears to reach the earth from all directions, giving rise to the familiar blue colour of the sky during the day.

735. Attenuation of Indirect Rays.—Attenuation will necessarily occur in the indirect rays since the atmosphere is not a perfect dielectric. The great ranges attained with small power on H.F. waves shows, however, that their attenuation in the atmosphere is much less than that in the surface of the earth. For H.F. waves the losses in the lower atmosphere are negligible, though they are a considerable cause of attenuation in the case of very L.F. indirect waves. The important attenuation of indirect H.F. waves takes place while they are travelling through the Heaviside Layer. This attenuation is roughly proportional to the density of free electrons. Thus it is greater by day than by night, and so night signals are stronger than day signals. It also varies inversely as the square of the frequency. Hence, other things being equal, the shorter the wave the less the attenuation. This helps to fix a lower limit to the frequencies which can be successfully used for long-distance transmission. The limits appear to be about 8,000 kc/s. for regular day transmission and 4,000 kc/s. for regular night transmission. Waves of low frequency suffer so great losses in transmission that they are useless for long distances unless exceptionally high power is developed in the transmitting aerial. These losses occur partly in the Heaviside Layer, and partly at the earth's surface when multiple reflection takes place. The great attenuation of H.F. waves at the earth's surface has previously been mentioned when considering the short range of the direct ray. In addition, unless the surface is perfectly plane, the wave will not be regularly reflected, and the energy will be scattered in various directions, so that only a small part is available for any particular transmission under consideration. This in itself almost limits long-distance transmission to rays which have only undergone one or two reflections at most at the earth's surface. The energy of these lower frequency waves cannot, of course, penetrate the Heaviside Layer, and so must be dissipated in some such manner as that described above before the wave reaches great distances from the transmitter. In the case of transmission over shorter distances at these frequencies, or of long-distance transmission at higher frequencies, the strength of a received signal at a particular point may thus depend very greatly on the conditions at a point half-way between it and the transmitter, *e.g.*, a jungle at a distance of 2,000 miles may render reception impossible at 4,000 miles on the same bearing.

736. Since in typical low-frequency transmission the attenuation increases with the frequency, and the reverse is the case for long-range high-frequency transmission, it would be expected that at some intermediate frequency minimum ranges would be obtained. This is actually the case, as shown in Fig. 440 by the curve of daylight range against frequency for constant energy radiation from the aerial. It will be seen that there is a decided falling off in range at frequencies between 1,000 and 2,000 kc/s., much larger, indeed, than would be expected from the considerations advanced above.



Variation of Daylight Range with Frequency.

FIG. 440.

An attempt has been made to explain this large attenuation by showing that at such frequencies the combined result of the fields of the wave and the earth's magnetic field is to produce a resonance effect in the motion of the free electrons in the Heaviside Layer. This motion then attains a large amplitude, the actual vibratory paths of the electrons being helices like the thread on a screw, and is damped by collisions with molecules. The energy necessary to maintain the motion is derived from the incident wave, which therefore suffers correspondingly large attenuation. This theory, however, seems to require that the effect should be greater by night than by day, whereas in practice the reverse is the case, the attenuation being much less marked at night.

737. Since the ionisation which constitutes the Heaviside Layer is mainly attributed to solar radiation, it is to be expected that considerable fluctuations in reception will occur when the signal passes from a transmitter in daylight to a receiver in darkness, and *vice versa.* In that part of the path where sunrise or sunset is occurring, the density of ionisation in the lower part of the layer is changing rapidly, and evidence of this is found in the large changes of signal intensity which occur at any particular receiving station under these conditions. The drop in signal intensity seems to be much greater when sunset occurs along the path than when it is night at the transmitter and day at the receiver.

738. Polarisation of Indirect Rays.—Changes in the nature of the polarisation of the indirect ray in its path through the Heaviside Layer are mainly attributed to the effect of the earth's magnetic field. Rotation of the plane of polarisation may take place, *i.e.*, the magnetic field vector ceases to be horizontal as it was in the incident wave, and circular polarisation may also be produced. At high frequencies these effects give rise to difficulties in direction-finding (Chapter XIX). Energy losses due to reflection at the earth's surface are greater when the electric field vector of the down-coming wave is parallel to the surface than when it is perpendicular.

739. Fading.—This is the name given to the occurrence of rapid fluctuations in signal intensity at a receiver. These may take place either at audio frequency or have a considerably longer period of one to four seconds. This latter kind is common on all frequencies, and is of smaller amount as the distance from the transmitter increases. Audio frequency fading is practically confined to frequencies above 400 kc/s. Between 500 and 1,000 kc/s. it is specially noticeable at night at distances of the order of 100 to 1,000 miles from the transmitter. It is violent at night for frequencies between 1,500 and 5,000 kc/s. at distances from the transmitter of 5 to 300 miles. At higher frequencies it occurs mainly at the edges of zones of reception.

Long period fading is presumably due to comparatively slow movements of the clouds of electrons forming the Heaviside Layer.

Audio frequency fading may be due to various causes. It is reasonable to suppose that the edges of zones of reception are not rigidly delimited but subject to small rapid fluctuation, corresponding to similar fluctuations in the effective height of the Heaviside Layer. In the case of overlapping zones, fading due to this cause would also occur. The field at a receiving aerial is the resultant of that due to the down-coming wave and its reflection from the earth's surface, and small fluctuations in phase of either of these will alter the relative amounts by which they assist or oppose each other. Two or more down-coming waves which entered the layer at different angles may be refracted so that they eventually arrive at the same point, and produce a similar effect on the total signal intensity owing to their varying phases. When the frequency and distance from the transmitter are such that both the direct and indirect rays are received with comparable intensities, changes in the phase of the indirect ray at the receiver will likewise cause it to assist or oppose the direct ray and produce fading.

740. More recent determinations of the equivalent height of the Heaviside Layer seem to provide evidence that there is not only one region in which bending of wireless waves takes place, but two distinct regions. The lower of these, at a mean height of about 60 miles, corresponds to the Heaviside Layer, its equivalent height increasing during darkness and falling rapidly at sunrise to its lower daytime value. Observations made on 750 kc/s. over short distances between transmitter and receiver, and therefore corresponding to steeply incident waves, indicated the presence of this region. Similar observations made on 3,000 kc/s., however, showed that the waves on occasion penetrated this region completely, and were turned back in another region of rich ionisation at rather more than twice the height (140 miles). This occurred always at night, and generally during the day also, but on some days the bending of the indirect ray took place in the lower (Heaviside) layer. Occasionally reflection from both layers occurred simultaneously, or successive observations at short (ten-minute) intervals showed reflection first at one equivalent height and then at the other. The large difference between the two equivalent heights rules out the idea that the change in the conditions is due to variations in ionisation, and seems to establish the existence of two separate densely-ionised regions. The lower layer is presumably the one whose density depends mainly on the sun's ultra-violet radiation, since its height varies with daylight and darkness. The theory has been advanced that the ionisation in the upper layer, which is more stable and permanent, is due to the emission from the sun of α-particles such as are shot out of radio-active substances.

It should be pointed out, however, that it has been found possible to attribute other experimental results of the same nature to multiple reflection between the Heaviside Layer and earth *i.e.*, without recourse to an explanation involving more than one densely ionised region in the upper atmosphere.

741. Atmospherics or Strays.—Since the beginning of the world, æther waves of the order of length used in wireless telegraphy have been continuously traversing its surface, but have only been noticed since the inception of wireless telegraphy.

They are generally known as "atmospherics," "strays," or "X's"; disturbances known as "statics" are a special variety.

Atmospherics have a very variable but generally long wavelength.

Their damping is heavy and their shock effect is severe.

When they encounter an aerial they set it oscillating at its own natural frequency and are consequently very difficult to cut out; they may be reduced in strength by the use of some limiting or balancing device, and as they are non-musical they can be over-read by a skilful operator provided they are not too severe.

The following is a brief summary of the known facts :—

Classification.—For convenience, atmospherics are classified as follows :—

- (*a*) **Hissing.** An almost continuous noise, especially marked during snow or when heavy clouds are passing over the aerial. (Hissing is not always due to atmospherics. It may occur by heterodyning of the carrier wave of an R/T signal.)
- (*b*) **Clicks,** or very short noises.
- (*c*) **Grinders,** a type exactly described by the word given.

The distinction between the various classes, however, does not correspond with any precise idea of their origin and is not always exact.

Annual Periodicity.—In general, atmospherics appear to be more frequent and severe in summer than in winter.

Actual measurements in England indicate a maximum in June and a minimum in March.

In the East Indies, the maxima occur during the changes of the monsoon. A minimum occurs during the N.E. monsoon and a less marked minimum during the S.W. monsoon.

Daily Periodicity.—As a rule, atmospherics are worst just before sunset till about 1 a.m., after which they gradually decrease. This effect varies, however, in different parts of the world.

Direction.—Atmospherics which have a distant origin, as opposed to those generated locally, appear to come from the direction of the equator.

More locally, atmospheric disturbances appear to have their origin in mountainous regions.

Nature.—Atmospherics have either the effect of a shock, *i.e.*, they produce in aerials an E.M.F. of short duration, reaching its maximum in a very short time, or else of a band of frequencies which it is impossible to eliminate by selective tuning. The former is of a similar type to that which would be produced by the sudden discharge of a condenser.

In general, the severity of atmospheric interference increases with decreasing frequency of the wave to which the receiving aerial is tuned, but observations made at Honolulu showed that stations working on a high frequency experienced numerous and violent disturbances, while neighbouring ones on lower frequencies were less troubled.

Experiments carried out to measure the shape and duration of the discharges have shown that they fall roughly under two headings —aperiodic and semi-periodic. The former are unidirectional and the latter have a second weaker impulse in the opposite sense to the first half-cycle.

Origin.—One class of atmospheric disturbance is due to lightning flashes of local origin.

As regards those coming from a distance, however, which occur even when the sky is perfectly clear, it has already been pointed out that the atmosphere is by no means at a uniform zero of potential, but that large patches of it accumulate excess positive and negative charges.

In addition to ionisation by the sun's rays, local action by wind or rain may also produce similar results.

For example, when a wind blows through cloud or rain, both are electrified, the water drops positively and the air negatively ; when this occurs on a large scale, several thousand feet above the earth's surface, in conditions favourable to the formation of large clouds, we get " thunder weather."

Again, evaporation is always accompanied by electrification of the liquid and vapour, so that in the tropics there is always a disturbed electrical state.

When, again, a wind blowing over a sandy or dusty plain raises clouds of dust, there is intense electrification. The potential of the dust, as a system of particles, is raised by their separation. The necessary energy is supplied by the wind.

Both positive and negative ions are formed which collect on the clouds and earth respectively, leading, when the potential difference is high enough, to lightning discharges between them.

742.—Statics.—Statics are a special variety of atmospherics, and are due to electrical charges accumulated by the aerial in the same way as those collected by a lightning conductor. A charged cloud approaching an aerial produces by static induction a charge of opposite sign in the aerial.

For this reason it is always inadvisable to leave an aerial insulated from earth by a receiving condenser, as a charge is liable to accumulate and puncture the condenser (para. **516**).