SCATTERING OF RADIO WAVES BY THE *F*-REGION OF THE IONOSPHERE

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Abstract—Records are reproduced showing diffuse echoes from the *F*-region of the ionosphere received continuously at night in equatorial regions over a wide range of wave-frequency. They are interpreted as due to Rayleigh scattering by spatial irregularities in the distribution of electron-density at or above a definite level in the *F*-region. Because of the highly dispersive nature of the ionosphere, there is no marked dependence of Rayleigh scattering upon wave-frequency such as there is for a non-dispersive medium. According to this interpretation, variation of the maximum wave-frequency to which diffuse echoes can be followed has nothing to do with variation of the maximum electron-density of an ionospheric region, but merely indicates variation in the size of irregularities in electron-density. Scattering of this type may have some bearing upon the phenomenon of persistence of *E*-region echoes to wave-frequencies greater than the critical penetration-frequency of the *E*-region.

Transient radio echoes from the *E*-region of the ionosphere attributable to temporary existence of marked scattering centers have been observed by Appleton, Naismith, and Ingram [see 1 under References at end of paper], by Eckersley [2], and by Appleton and Piddington [3]. Lateral deviation of radio waves attributable to scattering of a more persistent nature has been observed by Ratcliffe and Pawsey [4], by Pawsey [5], and by Martyn and Green [6]. The purpose of this note is to describe echoes which seem attributable to scattering from the *F*-region of the ionosphere. They have been received continuously at night in equatorial regions over a wide range of wave-frequency.

Figures 1, 2, and 3 show ionospheric records obtained at the Observatory maintained near Huancayo, Peru, by the Department of Terrestrial Magnetism of the Carnegie Institution of Washington. They were made by the automatic multifrequency technique of vertical radio sounding of the ionosphere [7]. The records show the way in which the virtual heights of ionospheric echoes vary with wave-frequency. Each record takes 15 minutes to make, during which time the wave-frequency changes continuously from 16.0 to 0.5 mc/sec. The four records of Figure 3 were made at intervals of 45 minutes, beginning before sunrise and continuing through the sunrise-period. Figure 3-*D* shows what may be regarded as a normal record. On it may be seen echoes from the *E*-region of the ionosphere at a height of about 100 km, and from the *F*-region at heights above 200 km. Multiple echoes due to reflection back and forth between the *F*-region and the Earth's surface may also be seen. Figure 3-*A* on the other hand shows a record of a very different character. On all wave-frequencies between about one and ten mc/sec echoes are obtained with virtual heights ranging upward from a minimum at about 420 km. Over this wide frequency-range there is little change in the character of the echoes. Their amplitudes decrease with increase of virtual height from a maximum at the lowest virtual height from which they are received. The amplitudes of the echoes are practically independent of wave-frequency up to a wave-frequency of about ten mc/sec. With further increase of wave-frequency, however, the echoes become weaker, and they disappear altogether at a wave-frequency between 11 and 12 mc/sec.

The phenomenon indicated in Figure 3-*A* has occurred at Huancayo to a greater or less extent almost every night during the winter of 1937-38.

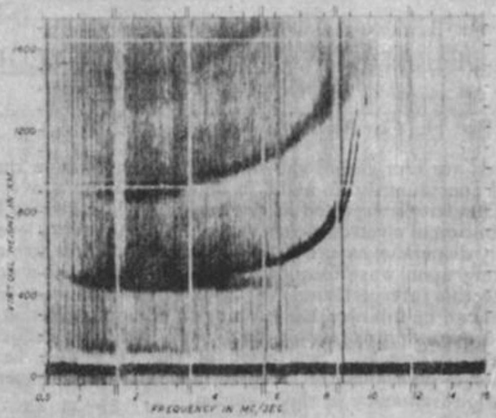

FIG. 1—RECORD SHOWING REGULAR AND DIFFUSE F-REGION ECHOES, HUANCAYO MAGNETIC OBSERVATORY, FEBRUARY 14, 1938, 20^h15^m–20^h30^m, 75° WEST MERIDIAN TIME

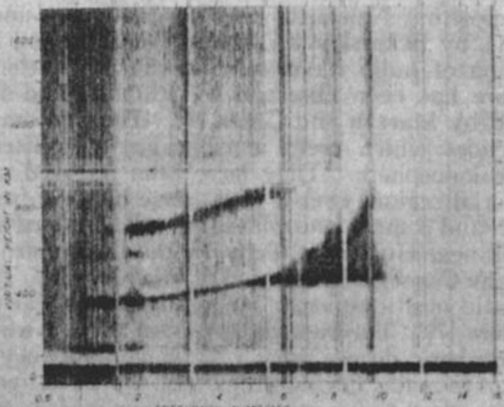

FIG. 2—RECORD SHOWING REGULAR AND DIFFUSE F-REGION ECHOES, HUANCAYO MAGNETIC OBSERVATORY, FEBRUARY 23, 1938, 21^h30^m–21^h45^m, 75° WEST MERIDIAN HOURS

There is no obvious correlation with magnetic activity. The phenomenon sets in between about $19^h\,00^m$ and $20^h\,00^m$, local time, in the manner indicated by the record reproduced in Figure 1. The onset of the phenomenon is closely correlated with a marked rise of 100 km or more in the height of the *F*-region between about $18^h\,00^m$ and $20^h\,00^m$, local time. The disappearance of the phenomenon seems to be correlated with subsequent decrease of the height of the *F*-region later in the night. On some occasions the *F*-region remains at a great height throughout the night. During the sunrise-period there is then a rapid fall in the height of the region, combined with a rapid increase in maximum electron-density. On these occasions the phenomenon indicated in Figure 3-*A* disappears in the manner indicated in Figure 3-*B*, 3-*C*, and 3-*D*. It will be noticed that in Figure 3-*B* and 3-*C* there is a frequency-range over which we obtain both the regular *F*-region echoes of Figure 3-*D* and the diffuse echoes of Figure 3-*A*. In this frequency-range the minimum virtual height of the diffuse echoes increases to infinity with decrease of wave-frequency. On the other hand the virtual heights of the regular *F*-region echoes increase to infinity with increase of wave-frequency in the usual way.

The maximum wave-frequency at which regular *F*-region echoes are obtained is the critical penetration-frequency of the *F*-region, and is a measure of the maximum electron-density in the region. For the record reproduced in Figure 3-*B*, the regular *F*-region echoes show that the maximum electron-density in the *F*-region was of the order of 10^5/cc. We may take it that, for the record reproduced in Figure 3-*A*, the maximum electron-density in the *F*-region was also about 10^5/cc. This is more than an order of magnitude less than that which would be required to give regular reflection up to a wave-frequency between 11 and 12 mc/sec, which is the wave-frequency up to which diffuse echoes can be seen in Figure 3-*A*. We shall therefore make no attempt to associate the diffuse echoes with any form of regular reflection, or to connect the maximum wave-frequency to which they can be followed with the maximum electron-density of an ionospheric region. On the contrary, we

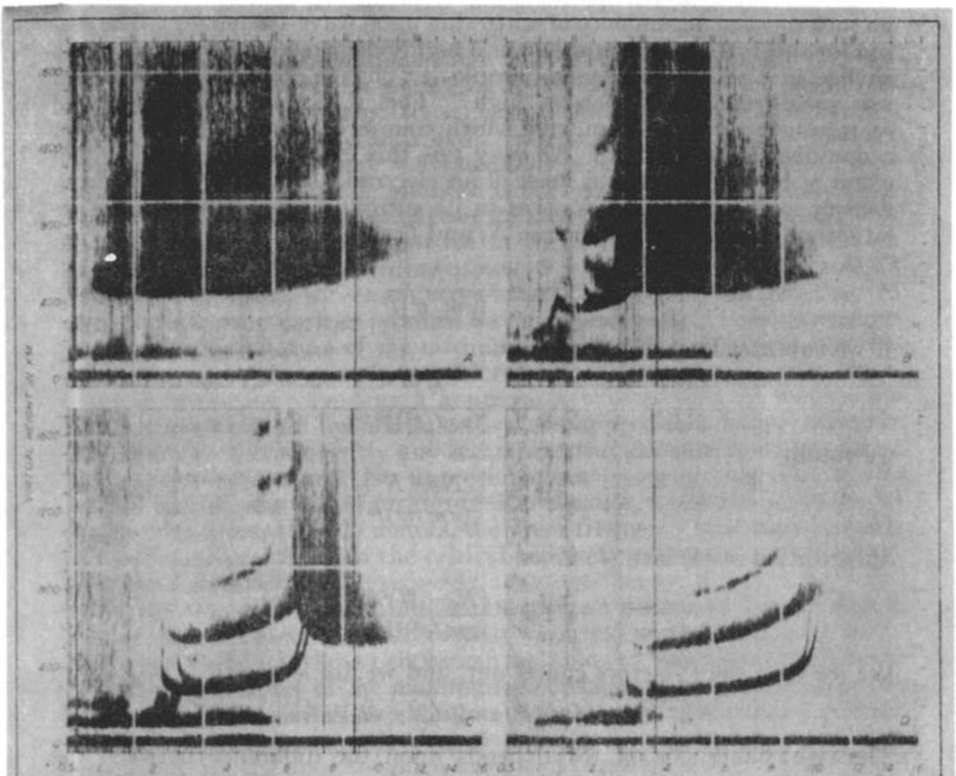

FIG. 3—RECORDS SHOWING REGULAR AND DIFFUSE F-REGION ECHOES, HUANCAYO MAGNETIC OBSERVATORY, FEBRUARY 10, 1938, (A) 04h45m–05h00m, (B) 05h30m–05h45m, (C) 06h15m–06h30m, (D) 07h00m–07h15m, 75° WEST MERIDIAN TIME

shall interpret the diffuse echoes as due to scattering by spatial irregularities in the distribution of electron-density in the F-region. Estimates of scattering produced by simple irregularities seem to indicate that enormous irregularities are not required in order to explain the diffuse echoes. We shall assume therefore that these echoes are due to existence in the F-region of electronic clouds, the maximum electron-density in which is not more that two or three times the average maximum electron-density in the F-region.

Consider a cloud of electrons in the ionosphere. Suppose that its linear dimensions are small compared with the wave-length of the radio wave. Let μ be the refractive index of the cloud, and μ_0 that of its surroundings. Suppose that there is incident upon the cloud a radio wave of frequency f and intensity I (proportional to square of amplitude). Then, if i is the intensity of the scattered wave, we have according to Rayleigh

$$i/I \propto f^4(\mu^2-\mu^2{}_0)^2 \tag{1}$$

As is well known, (1) shows that, for a non-dispersive medium, the intensity of the scattered wave increases markedly with increase of wave-frequency, being proportional to f^4. For the ionosphere, however, there is no such marked dependence of scattering upon wave-frequency. The reason for this is that the ionosphere is a highly dispersive medium. A given change in electron-density causes a larger change in refractive index at low wave-frequencies than at high. This produces a dependence of scattering upon wave-frequency which counterbalances that existing for a non-dispersive medium. We may put this explicitly as follows. Let e and m be the charge and mass of an electron. Let N be the electron-density in the cloud and N_0 that in its surroundings. The simplest relation we can assume between μ, N, and f is

$$\mu^2 = 1 - \frac{N}{(\pi m/e^2)f^2} \tag{2}$$

If we subtract from (2) the equation

$$\mu^2{}_0 = 1 - \frac{N_0}{(\pi m/e^2)f^2} \tag{3}$$

we obtain

$$\mu^2 - \mu^2{}_0 = \frac{N_0 - N}{(\pi m/e^2)f^2} \tag{4}$$

Substitution of (4) into (1) gives

$$i/I \propto f^4 \frac{(N_0 - N)^2}{(\pi m/e^2)^2 f^4} \tag{5}$$

We see that the f^4-factors cancel out, and we are left with

$$i/I \propto (e^2/\pi m)^2 \, (N - N_0)^2 \tag{6}$$

The right-hand side of (6) depends upon the difference between the electron-density in the cloud and that in its surroundings, but is independent of wave-frequency. For the actual ionosphere there will, as a matter of fact, be some dependence of scattering upon wave-frequency.

This is partly because the dependence of intensity of scattered wave upon refractive index is a little more complicated than is indicated by (1), and partly because the dependence of refractive index upon wave-frequency is a little more complicated than is indicated by (2). But the salient fact remains that, for Rayleigh scattering of radio waves by the ionosphere, there should be no marked dependence upon wave-frequency.

We have already mentioned that, for the record reproduced in Figure 3-*A*, there is no marked dependence of the character of the echoes upon wave-frequency over the wide frequency-range from one to ten mc/sec. This would agree with the hypothesis that these echoes are due to Rayleigh scattering by spatial irregularities in the distribution of electron-density in the *F*-region. The question arises however as to why at higher frequencies the echoes become weaker, and disappear altogether at a wave-frequency between 11 and 12 mc/sec.

The theory of Rayleigh scattering assumes that the linear dimensions of scattering centers are small compared with the wave-length of incident radiation. The theory of Rayleigh scattering by the ionosphere therefore assumes that the linear dimensions of irregularities in electron-density are small compared with the wave-length of incident radio waves. As the wave-frequency increases, however, the wave-length decreases. With sufficient increase of wave-frequency, the wave-length must become comparable with the linear dimensions of irregularities in electron-density. We therefore interpret the wave-length corresponding to the maximum wave-frequency to which scattered echoes can be followed as indicating the linear dimensions of the irregularities in electron-density. For the record reproduced in Figure 3-*A*, the maximum wave-frequency to which the scattered echoes can be followed is between 11 and 12 mc/sec. The corresponding wave-length is about 25 meters. We therefore interpret Figure 3-*A* as indicating existence in the *F*-region of irregularities in electron-density, the linear dimensions of which are of the order of 25 meters. For radio waves of wave-length appreciably longer that 25 meters, these irregularities produce Rayleigh scattering. This, on account of the dispersive nature of the medium, is practically independent of the extent by which the wave-length exceeds 25 meters. On the other hand, for radio waves of wave-length appreciably shorter than 25 meters, the linear dimensions of the irregularities are appreciably larger than the wave-length. Consequently any scattering they produce is accomplished by ordinary refraction. No appreciable scattering of this type occurs for the record reproduced in Figure 3-*A* because, when the wave-length is appreciably less than 25 meters, the wave-frequency is at least an order of magnitude greater than the critical penetration-frequency even of the electronic clouds.

If the above interpretation of the diffuse echoes of Figure 3-*A* is correct, it is important to notice that variation of the maximum wave-frequency to which these echoes can be followed has nothing whatever to do with variation of the maximum electron-density of an ionospheric region. It merely indicates variation in the size of the scattering centers. It seems possible that scattering of the type here postulated may also have some bearing upon the phenomenon of persistence of *E*-region echoes to wave-frequencies greater than the critical penetration-frequency of the *E*-region.

The records seem to indicate that irregularities in electron-density do not in general exist throughout the entire F-region, but only at or above a definite level in the F-region. For the record reproduced in Figures 1, 2, and 3, this level is about 420 km. We interpret echoes of minimum virtual height in Figure 3-A as ones which, after having travelled vertically up to a height of about 420 km, have been scattered backwards, and have then travelled vertically back to the equipment. Echoes of greater virtual height we interpret as ones which have travelled up to, and back again from, the same scattering-level at a height of about 420 km, but at some angle to the vertical. For example, an echo of virtual height three-halves the minimum virtual height is one which has travelled at an angle $\cos^{-1}(2/3)$ to the vertical.

We have now to explain why, for the records reproduced in Figure 3-B and 3-C, there is a frequency-range over which we obtain not only the regular F-region echoes but also the scattered echoes, and why the minimum virtual height of the scattered echoes increases continuously to infinity with decrease of wave-frequency. In Figure 4 is shown what we may regard as an east-west cross-section of the F-region of the iono-

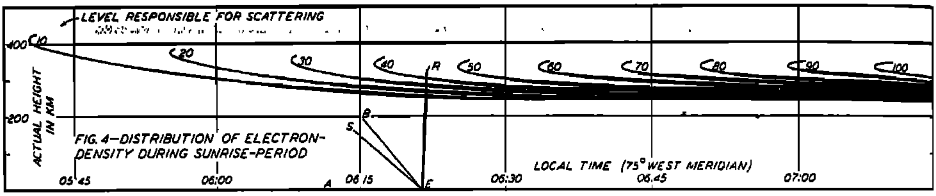

FIG. 4—DISTRIBUTION OF ELECTRON-DENSITY DURING SUNRISE-PERIOD

sphere by a vertical plane through Huancayo during the sunrise-period on February 10, 1938. The curves represent surfaces of equal electron-density. The numbers attached to the curves are proportional to electron-density. This Figure was deduced in the following way: From the records reproduced in Figure 3, together with intervening records not reproduced, we deduced by interpolation the variation of virtual height with wave-frequency which would have been obtained for the regular F-region echoes every 15 minutes if simultaneous observations had been made over the entire frequency-range. To the series of curves thus obtained we fitted, by a method of least squares, parabolic maxima of electron-density, neglecting the possible effect of the Lorentz polarization-correction. We then represented the variation with time of the distribution of electron-density with height by means of the contours shown in Figure 4. The curves are incomplete because the records give information about the distribution of electron-density only below the level of maximum electron-density. The scales in Figure 4 have been so chosen that 15 minutes on the horizontal scale is equivalent to 400 km on the vertical scale. Now, at the equator, sunrise advances westwards about 400 km every 15 minutes. Consequently, if we neglect curvature of the Earth's surface, we may regard Figure 4 as giving an approximate east-west cross-section of the ionosphere through Huancayo. The equipment may be regarded as moving from left to right along the horizontal axis at the rate of 400 km every 15 minutes, its position relative to the distribution of electron-density at any time being as indicated. It will be seen that, during the sunrise-period, the surfaces of equal electron-density above Huancayo are by no means horizontal. This is why, for the records reproduced in Figure 3-*B* and 3-*C*, there is a frequency-range over which we obtain both regular *F*-region echoes and scattered echoes. The level responsible for scattering is indicated in Figure 4 by shading. The point *E* indicates the position of the equipment relative to the distribution of electron-density at the moment when the wave-frequency 6.5 mc/sec was being radiated for the record reproduced in Figure 3-*C*. *ER* indicates the path of the regular *F*-region echo. *AEB* indicates the angle within which the scattered echoes are being received. Scattered echoes received in the direction *AE* would obviously have an infinite virtual height. Scattered echoes received in the direction *BE* would also have an infinite virtual height because they are only just penetrating the ionization which exists below the level responsible for scattering. Consequently there is a direction *SE* which gives the minimum virtual height of the scattered echoes at this wave-frequency. With decrease of wave-frequency the angle *AES* decreases. Consequently the minimum virtual height of the scattered echoes increases as shown in the record reproduced in Figure 3-*C*. It may be mentioned that at the top of this record there may be seen echoes which seem to be due to scattering subsequent to regular reflection back and forth between the *F*-region and the Earth's surface.

The increase to infinity of the minimum virtual height of the scattered echoes of Figure 3-*C* with decrease of wave-frequency is an indication that the level responsible for scattering was above the level of maximum electron-desity in the *F*-region as shown in Figure 4. For the records reproduced in Figures 1 and 2, however, there is no increase to infinity of the minimum virtual height of the scattered echoes with decrease of wave-frequency. (Such increase as exists in Figure 1 at wave-frequencies less that 1.5 mc/sec is due, of course, to the effect of ionization in the *E*-region.) We interpret this as indicating that the level responsible for scattering was below the level of maximum electron-density in the *F*-region.

The situation above Huancayo during most evenings of the winter of 1937-38 would seem therefore to have been as follows. Between about $18^h\,00^m$ and $19^h\,00^m$, local time, there are irregularities in electron-density at or above a certain level which is higher than the level of maximum electron-density in the *F*-region. But the size of the irregularities in electron-density is too large to allow appreciable scattering to take place at wave-frequencies greater than the critical penetration-frequency of the *F*-region. Between about $18^h\,00^m$ and $20^h\,00^m$, local time, the height of the *F*-region increases by 100 km or more. During this period the level of maximum electron-density ascends to a height considerably greater than that at or above which irregularities in electron-density exist, and a level where scattering takes place is revealed as indicated by the record reproduced in Figure 1. If the size of the irregularities in electron-density decreases and the height of the *F*-region also decreases, we obtain a record of the type reproduced in Figure 2. But if the height of the *F*-region fails to decrease until sunrise, we obtain records of the type reproduced in Figure 3.

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