THE INTERPRETATION OF SOME OBSERVATIONS OF RADIO WAVES SCATTERED FROM THE LOWER IONOSPHERE

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Abstract

Possible shapes and spatial scales of ionospheric irregularities in the lower ionosphere have been determined from analyses of two sets of radio wave back-scattering observations: measurements of the spatial scale of the ground pattern of the wave field back-scattered from altitudes near 95 km and measurements of the amount and angular distribution of power back-scattered from solitary horizontally-moving irregularities at altitudes near 75 km. At 95 km the irregularities are anisotropic, with larger horizontal than vertical dimensions. For an assumed Gaussian distribution of ionization, the inferred axial ratio (horizontal to vertical) is about three. It is tentatively concluded that the irregularities at 75 km are sharply bounded and are some kilometres in horizontal extent.

I. INTRODUCTION

Weakly ionized irregularities in the lower ionosphere ($\sim$50–110 km) are responsible for a number of phenomena observed by radio waves. Amongst these are the forward scatter of v.h.f. signals over large distances, the presence of the so-called diffuse sporadic-*E* observed on occasions by ionosondes, and the partial reflections of medium frequency signals from the *D*-region. These irregularities have been studied extensively in recent years by a variety of radio and rocket borne techniques. Observations of the irregularities associated with the diffuse type of sporadic-*E* layers at heights above 90 km by sensitive rocket probes have shown, for example, that the vertical scale of the irregularities is of the order of some tens of metres (Reddy 1968). Because of the higher values of collision frequency and the much lower electron densities, observations of irregularities in the *D*-region are more difficult to make, and there has been much discussion about the nature of the irregularities responsible for the partial reflection observed at medium frequencies (see the review by Belrose 1970).

It is probable that the *D*-region irregularities have a wide range of scales and shapes. On some occasions, phase path observations show the existence of sharply bounded reflectors of very large horizontal dimensions (Smith *et al.* 1965; Fraser and Vincent 1970). More often, only a small number of irregularities of limited dimensions (but still larger than a wavelength) may be involved at any one time (Austin and Manson 1969). On other occasions it is possible that much smaller (compared with a wavelength) irregularities are required to explain the observations (volume scattering). One feature which should be mentioned, however, is that, at least in the southern hemisphere, the scattering regions are often limited in vertical extent so that, whether many or only a few irregularities are involved, the lower ionosphere often appears to be horizontally stratified (Gregory 1961).

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Because of the evidence which suggests that several distinct types of irregularities are responsible for the scattering it is difficult to describe uniquely how the ionization is distributed. It is obviously important to know more about the dimensions and shapes of the scatterers to obtain a better understanding of the dynamics of the mesosphere and lower thermosphere. It is also important for any future refinements of data reduction techniques for the determination of *D*-region electron densities by the Differential Absorption Experiment (hereinafter referred to as DAE).

One way in which the scattering medium can be described is to assume that it is random and then characterize the spatial scales of the medium in terms of a spatial autocorrelation function (Booker 1959). In many cases, however, it is more convenient to characterize it in terms of a particular model for the individual scatterers, which is an approach used by Moorcroft (1961) to study high frequency back-scatter from auroral ionization. This approach is adopted in the preceding paper by Briggs and Vincent (1973, present issue pp. 805–14; hereinafter referred to as Paper I), who give a general discussion of some of the factors involved in remote sensing of the environment. One advantage of this approach is that many of the properties (such as the angular distribution of scattered radiation) of a particular model remain the same whether only one or many scatterers are involved. By comparing the properties of particular models of scattering irregularities with the experimentally measured properties it should be possible to build up a realistic picture of the irregularities.

In the present paper, results derived in Paper I are used to analyse data from two sets of observations of scattering from the lower ionosphere. Our aim is to establish what can be determined about the observed irregularities in the light of current knowledge of the neutral and ionized atmosphere. The first set of observations, considered in Section II, comprise measurements of the spatial autocorrelation function of the diffraction pattern produced on the ground by weak scatterers situated at heights near 95 km. The second set of observations, considered in Section III, comprise measurements of the angular distribution and strength of energy scattered from single horizontally-moving irregularities in the *D*-region. The findings are discussed in Section IV.

II. Measurements of Spatial Correlation Functions

It is shown in Paper I that, when waves are scattered from a random distribution of irregularities, the correlation function of the spatial variations of the wave field on the ground is determined by a number of factors which include the polar diagrams of the transmitting and receiving aerials, the space attenuation of the waves, and the way in which the irregularities themselves scatter the incident energy. It is also shown that the complex spatial autocorrelation function of the ground pattern is given by

$$\rho(\alpha') = K_0 \int_0^\infty \mathscr{T}(s)\,\mathscr{R}(s)\,|F(s)|^2\, s^2 \mathrm{J}_0(2\pi\alpha' s)\,\mathrm{d}s, \tag{1}$$

where s is the sine of the angle from the zenith, α' is the separation of the observing points measured in units of the wavelength λ, K_0 is a normalizing constant, $\mathscr{T}(s)$ and $\mathscr{R}(s)$ are the power polar diagrams of the transmitting and receiving aerials respectively, and J_0 is the Bessel function of zero order. The function $|F(s)|^2$, which describes how the irregularities themselves scatter the power, is referred to here as the "shape factor" because of its similarity to a parameter in X-ray crystallography, which also depends on the scale and shape of the irregularities.

The scattering of radio waves from the ionosphere is caused by variations in refractive index, which are assumed here to arise from irregularities in the electron density. Consequently, the spatial scales of the electron density irregularities can be estimated from a comparison of the experimentally measured correlation functions with theoretical values calculated by means of equation (1).

The measurements were made using the large antenna array at the Buckland Park field station of the University of Adelaide (34° 38′ S, 138° 28′ E). The array consists of 89 pairs of crossed half-wave dipoles suspended 11 m above the ground. The aerials are resonant at a frequency of $1\cdot98$ MHz ($\lambda = 150$ m) and the basic array spacing is $91\cdot4$ m or $\sim 0\cdot61\,\lambda$. Each aerial is connected to its own receiver at a central recording laboratory and the signals from each receiver were sampled at the rate of 5 s^{-1}, digitized to 64 levels, and recorded on magnetic tape. The transmitting antenna consists of four half-wave folded dipoles arranged in the form of a square and suspended 30 m above the ground. The transmitter pulse length was 30 μs and the echoes were selected by a time gate of duration equivalent to a range interval of 5 km. The transmitting antenna was connected in a sense appropriate to the extraordinary mode of polarization for the night time observations and the ordinary mode for the day time observations. The correlation coefficients were calculated on a computer using the two-dimensional spatial correlation analysis devised by Briggs (1968). The method of analysis and more detailed information about the recording techniques used in this experiment are given by Felgate and Golley (1971).

The observations were made in July 1970 and refer to the height range 90–100 km, the lowest altitudes at which measurements can usually be taken with the present equipment. The majority of the observations were made between 00^{h} and 08^{h}, so that the echoes mainly came from what is known as the night *E*-region. Most of the two-dimensional correlation functions had contours of constant correlation which were approximately circular, i.e. the ground pattern was almost isotropic although some elongation was occasionally noted. From a limited number of observations, Felgate and Golley (1971) also found that the ground patterns formed by *D*-region partial reflections were essentially isotropic. Figure 1(*a*) shows experimental values of the mean correlation of amplitude ρ_{A} as a function of receiver separation α', averaged over all orientations of receiver pairs. The vertical bars indicate the spread of values at given separations. It is apparent that the mean pattern size, defined as the separation at which ρ_{A} has fallen to $0\cdot5$, is $\sim 0\cdot8\,\lambda$, or ~ 120 m. This value agrees very well with the value quoted by Felgate and Golley for their partial reflection observations, which also refer to heights near 90–95 km. It is, however, slightly larger than the mean value of 105 m found by Golley and Rossiter (1970) who also used the Buckland array but employed a somewhat different technique. There does not appear to be a significant variation in the average ground pattern size of radio waves scattered from heights near 95 km for either the day or night time ionosphere.

In order to compare these results with theoretical curves computed using equation (1) a number of assumptions were made. It was assumed that the polar diagrams $\mathscr{T}(s)$ and $\mathscr{R}(s)$ of the aerials were given by the usual expressions for arrays of half-wave dipoles standing above a perfectly conducting ground plane. The choice of the functional form for the irregularities was more difficult. One possibility was to assume that on the average the electron density varies radially in a Gaussian fashion from the centre of each irregularity. This gives a value for the excess density over the ambient value of the form

$$N = N_0 \exp(-(x^2+y^2)/a^2 - z^2/b^2), \tag{2}$$

where N_0 is the value at the centre of the irregularity, x and y are the horizontal

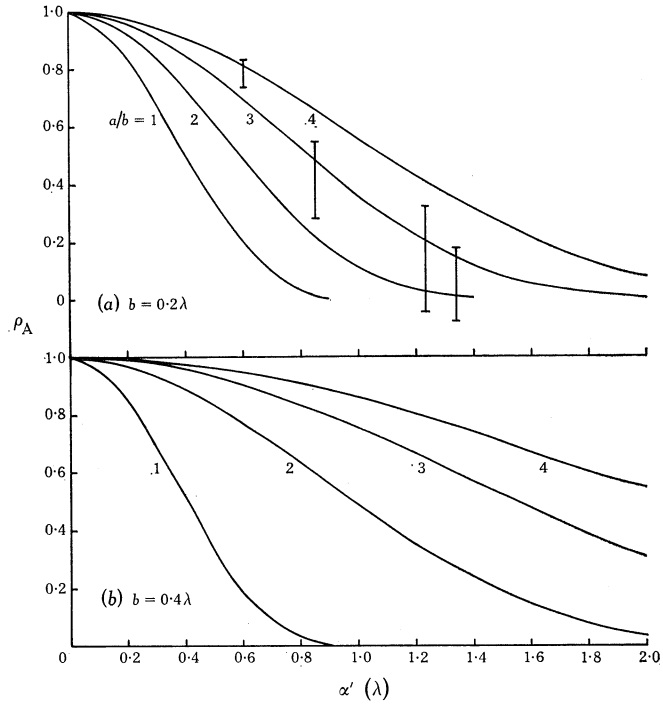

Fig. 1.—Experimental and theoretical plots of the autocorrelation ρ_A for backscattering from Gaussian irregularities, shown as functions of the receiver separation α', the indicated axial ratios a/b, and the vertical scales (*a*) $0 \cdot 2\lambda$ and (*b*) $0 \cdot 4\lambda$. The vertical bars in (*a*) indicate the range of observed values at given receiver separations.

coordinates, and z is the vertical coordinate. This is the shape the irregularities might have if diffusion is important in the lower ionosphere but takes place at different rates in the horizontal and vertical direction. It is shown in Paper I that Gaussian irregularities scatter energy such that for a constant axial ratio ($b \propto a$)

$$|F(s)|^2 \propto b^6 \exp(-8\pi^2\lambda^{-2}\{b^2+(a^2-b^2)s^2\}). \tag{3}$$

Substituting expression (3) for $|F(s)|^2$ and standard expressions for $\mathscr{T}(s)$ and $\mathscr{R}(s)$ into equation (1) enables the function $\rho(\alpha')$ to be evaluated by numerical integration. It should be noted that equation (1) gives the autocorrelation function for the complex wave field, while the experimental values cited here are for amplitude only. Providing the scattered waves are randomly phased and there is no superimposed specular component (an assumption which is probably satisfied for the present observations as only records showing deep fading were analysed) then it can be shown that the autocorrelation of the amplitude pattern is given by $\rho_A(\alpha') = \{\rho(\alpha')\}^2$ (Ratcliffe 1956). Curves for $\rho_A(\alpha')$ are plotted in Figures 1(*a*) and 1(*b*) for various values of the axial ratio a/b and two values of the vertical scale size b. It is apparent that the scale of the curves is dependent on both a/b and b, which makes the matching of the experimental and theoretical curves difficult. However, it is shown in Paper I that Gaussian irregularities with values of $b \approx 0 \cdot 2\,\lambda$ are the most efficient when back-scattering is involved and it is therefore likely that the present experiment preferentially selects those irregularities with vertical scales of the order of 30 m. Bowhill (1966) has reported rocket measurements which show irregularities having Gaussian scale sizes of this order of magnitude and amplitudes of the order of 5% to 10% of the ambient density. Other rocket observations show that these weak irregularities are a common feature of the lower *E*-region (Smith 1966; Mukunda Rao and Smith 1968). If the vertical scale is fixed at $\sim 0 \cdot 2\,\lambda$ then the curves can be compared directly with the observed values of ρ_A as is shown in Figure 1(a). It is apparent that a curve for an axial ratio ~ 3 fits the data best which means that the irregularities are elongated horizontally like discs and have horizontal scales of the order of 90–100 m.

Of course it is possible that the choice of equation (2) to represent the irregularity could be wrong. Nevertheless one important point can be made: the curve for $a/b = 1$ (isotropic irregularities) is independent of the size and radial variation of electron density since this curve depends only on the characteristics of the transmitting and receiving antennas. As it does not match the results we must conclude that the irregularities are certainly anisotropic, with horizontal dimensions greater than their vertical dimensions.

III. Scattering from Single Irregularities

The shape and size of ionospheric irregularities determine the angular variation of the back-scattered energy. The scale of the spatial autocorrelation function of the wave pattern on the ground is determined by this angular distribution if many irregularities are present simultaneously (see Paper I). Obviously, if it is possible to determine the angular distribution directly for a *single* irregularity then it should also be possible to determine the form of such an irregularity.

Fraser and Vincent (1970) have reported observations of a certain type of *D*-region scatterers. The observations were made at Christchurch, New Zealand (44° S), and both amplitude and phase techniques were used. On occasions, the phase variations of the returned signals showed that the echoes were coming from single horizontally-moving irregularities. These irregularities were usually observed in the altitude range 70–80 km and it was shown that they could be observed out to angles of $\sim 10°$ from the zenith. Similar irregularities have also been observed at Adelaide. Another characteristic of these irregularities is that they have equivalent (Fresnel) reflection coefficients of the order of 10^{-4}, which is in agreement with other measurements of partial reflections at this altitude (Austin and Manson 1969; Manson *et al.* 1969).

In order to make experimental and theoretical comparisons it is convenient to consider the irregularities as targets and express results in terms of their radar differential cross section σ, which is a measure of the power scattered in unit solid angle per unit incident power. To do this it is necessary to convert from the reflection coefficient

R_f to σ. The reflection coefficient is calculated by assuming that the reflections come from a horizontally stratified layer so that if the transmitting antenna has a half-power beam width of θ_0 then the received power density on the ground is given by (Austin and Manson 1969)

$$E = P_T R_f^2 / h^2 \pi \theta^2 , \tag{4}$$

where P_T is the transmitted power and h is the height of the reflector. If the receiving antenna has an effective area of A_e and the usual assumption is made that the gain of the transmitting antenna is given by $4\pi\theta_0^{-1}$ then the total received power is

$$P_R = P_T R_f^2 \, G A_e / 4\pi^2 h^2 . \tag{5}$$

For the case of a single irregularity the received power is related to the scattering cross section by the radar equation

$$P_R = (P_T G / 4\pi h^4) A_e \sigma . \tag{6}$$

From equations (5) and (6) we have

$$\sigma = \pi^{-1} h^2 R_f^2 . \tag{7}$$

If we confine our attention to situations in which $5 \times 10^{-5} \leqslant R_f \leqslant 5 \times 10^{-4}$ then, from equation (7), we have $4 \lesssim \sigma \lesssim 400 \text{ m}^2$ if the mean height of the observations is taken to be 75 km.

The single irregularities observed by Fraser and Vincent (1970) may be characterized by the facts that they can back-scatter a significant amount of power over angles of $\sim 10°$ (the power falls to one-half of the overhead value at $\sim 5°$) and their equivalent cross section is $\sim 10 \text{ m}^2$.

Theoretical back-scatter cross sections may be calculated in a number of ways. We assume that the irregularity is at such a range that it is illuminated by an essentially uniform wave field. Then by using an approach similar to that described by Booker (1959) it is possible to show that the scattering cross section is given by

$$\sigma = (k^2/4\pi)^2 \, |(\Delta\varepsilon/\varepsilon)_0|^2 \, |F(s)|^2 , \tag{8}$$

where $k = 2\pi\lambda^{-1}$, $(\Delta\varepsilon/\varepsilon)_0$ is the fractional change in permittivity at the centre of the irregularity, and $F(s)$ is the Fourier transform of the function which describes how the permittivity varies throughout the irregularity. For scattering in the ionosphere we have $\Delta\varepsilon/\varepsilon = 2\Delta n/n$, where $\Delta n/n$ is the fractional change in refractive index. At high frequencies it is possible to use the approximation

$$n^2 \approx 1 - \pi^{-1} r_e N \lambda^2 , \tag{9}$$

where r_e is the classical radius of the electron, so that

$$|2\Delta n/n| \approx \pi^{-1} r_e \lambda^2 \Delta N . \tag{10}$$

Substituting the expression (10) for $(\Delta\varepsilon/\varepsilon)_0$ in equation (8) gives

$$\sigma_0(s) \approx r_e^2 \Delta N_0^2 |F(s)|^2 , \tag{11}$$

where ΔN_0 is the value of the excess electron density at the centre of the irregularity and σ_0 is the cross section for back-scattering of h.f. radio waves (the case of no magnetic field and no collisions).

An obvious first choice for the distribution of density is the Gaussian form (2) which leads to

$$\sigma_0(s) = r_e^2 \,\Delta N_0^2\, V_b^2 \exp\bigl(-8\pi^2\lambda^{-2}\,\{b^2+(a^2-b^2)s^2\}\bigr), \tag{12}$$

where $V_b = \pi^{3/2}a^2b$. Since the total number of electrons N_t in a Gaussian irregularity is given by $\Delta N_0\, V_b$, equation (12) reduces to

$$\sigma_0(s) = r_e^2\, N_t^2 \exp\bigl(-8\pi^2\lambda^{-2}\,\{b^2+(a^2-b^2)s^2\}\bigr). \tag{13}$$

It is apparent that the cross section is equal to the power scattered from each free electron, modified by the overall shape of the irregularity (Moorcroft 1961).

In the case of scatter from the *D*-region, however, the probing frequencies used are such that the influence of both the Earth's magnetic field and of collisions is important and must be taken into account. The effect of the magnetic field is to split a linearly polarized radio wave entering the ionosphere into extraordinary and ordinary characteristic modes, which at mid and high geomagnetic latitudes are essentially circularly polarized. At the frequencies usually used in partial reflection experiments the back-scatter cross sections are larger for the extraordinary than for the ordinary wave. The effect of collisions between electrons and neutral constituents is to both restrict and randomize the motions of the electrons moving under the influence of the incident radio waves, thereby reducing the efficiency with which the irregularities scatter the wave energy. However, to take account of these effects, it is necessary to use more complicated expressions for the refractive index than that used in equation (11), so that it is not possible to give a relatively simple expression for σ as in (13). Calculations of the ordinary and extraordinary mode cross sections for conditions pertaining to those at Christchurch were made using the generalized magnetoionic refractive index derived by Sen and Wyller (1960). A frequency of $2\cdot4$ MHz was assumed and the results were normalized to the high frequency value for the cross section σ_0. The normalized back-scattering cross sections are plotted in Figure 2 as a function of height. It is apparent that collisional effects are important at heights below $\sim$75 km. It is important to note that the effects of absorption would normally cause the extraordinary signals to be more strongly attenuated by midday at heights above 70–75 km and so the ordinary mode echoes dominate at greater heights. The calculations show that irregularities at these greater heights scatter ordinary mode signals at frequencies of $\sim 2\cdot5$ MHz with efficiencies of only $\sim 0\cdot4$ of the high frequency value.

Taking into account the efficiency factor of $\sim 0\cdot4$ enables the observations to be compared with theoretical models of the irregularities. Initially we assume that a Gaussian model is appropriate and use equation (13) to calculate the cross sections. Since the cross sections are a function of the dimensions of the irregularities as well as the angle of inclination of the wave to the axis of symmetry, it is necessary to make some assumption about these factors. As outlined in Section II it seems most appropriate to assume that $b \approx 0\cdot2\,\lambda$, or $\sim$25 m in the present case, which enables the cross sections to be calculated for various scattering angles as a function of the axial ratio a/b. Three such curves, shown in Figure 3, demonstrate that only irregularities with axial ratios of 5 or less can back-scatter significant amounts of energy over angles greater than 5°. If the Gaussian assumption is appropriate then the horizontal dimensions of the irregularities must be $\lesssim 1\,\lambda$, that is, $\sim$125 m for the Christchurch observations.

It is now a straightforward matter to substitute the derived values for a and b in equation (12) and so calculate the maximum value of the cross section, provided that the value of ΔN_0 is known. Although no direct measurement of the electron density deviations has been reported from Christchurch, it is possible to estimate a probable value for ΔN_0. Gregory and Manson (1969) have reported measurements of electron densities made at Christchurch by the DAE at about the time the observations under discussion were made. They show that a typical value for the ambient electron density at 75 km is $\sim 300\ \mathrm{cm}^{-3}$, which is in agreement with other observations at mid-latitude stations under quiet conditions (Maeda 1971; Mechtly *et al.* 1972).

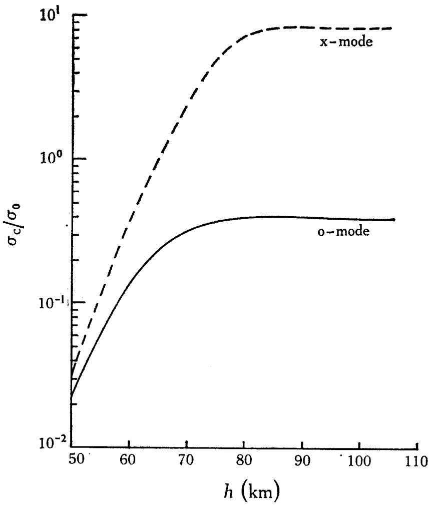

Fig. 2.—Variation with altitude h of both the ordinary and extraordinary mode scattering cross sections σ_c at 2·4 MHz relative to the cross sections σ_0 in the high frequency limit.

Studies of highly sensitive rocket measurements of electron density made elsewhere have shown that density fluctuations rarely exceed more than 10% of the background value (Manson *et al.* 1969) and so for convenience we assume here that ΔN_0 is about 10% of the ambient value, that is, $30\ \mathrm{cm}^{-3}$.

Equation (12) may now be evaluated to yield, in the high frequency limit, at vertical incidence ($s = 0$)

$$\sigma_0 \approx 1\cdot 4 \times 10^{-3}\ \mathrm{m}^2 .$$

This value may be expected to be reduced by the efficiency factor of $\sim 0\cdot 4$ at the observing frequency 2·4 MHz. Obviously values of 10^{-4}–$10^{-3}\ \mathrm{m}^2$ are much less than the observed values of $\sim$1–10 m^2. Even if 100% variations in the electron density are assumed, the calculated value is only $\sim 10^{-1}\ \mathrm{m}^2$, still well below the observed values. It is apparent that the observations of single isolated irregularities cannot be explained by a Gaussian model for the density distribution of the irregularities and consequently it appears that some other model must be invoked.

An alternative proposal for the density distribution of the irregularities is an ellipsoidal blob model in which the density is uniformly distributed as

$$\Delta N = \Delta N_0 \quad \text{inside} \qquad \text{and} \qquad \Delta N = 0 \quad \text{outside}$$

of an ellipsoidal surface defined by

$$(x^2+y^2)/a^2+z^2/b^2 = 1\,. \tag{14}$$

This model presupposes that such a sharply bounded irregularity can be generated in the mesosphere and that, once it exists, its boundaries do not diffuse significantly over the period of observation, a supposition which will be considered in Section IV below.

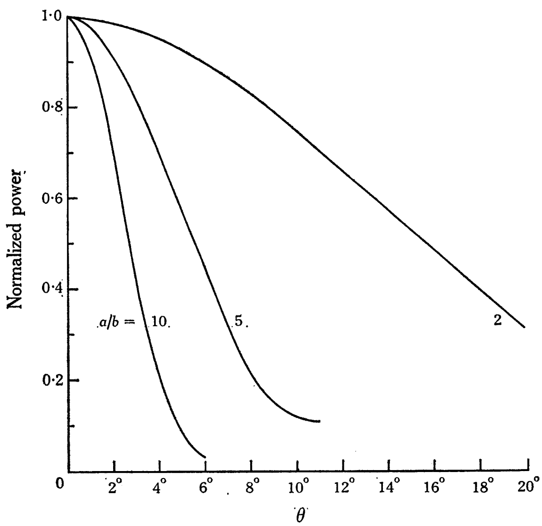

Fig. 3.—Relative back-scattered power for Gaussian irregularities, shown as a function of the off-vertical angle θ and the indicated axial ratios a/b.

The shape factor for such an irregularity can be shown to be (Hoseman and Bagchi 1962)

$$|F(s)|^2 = |3\,V_b\,\{(\sin\zeta - \zeta\cos\zeta)/\zeta^3\}|^2\,, \tag{15}$$

where

$$V_b = \tfrac{4}{3}\pi a^2 b \qquad \text{and} \qquad \zeta = 4\pi\lambda^{-1}\,\{b^2+(a^2-b^2)\}^{\frac{1}{2}}\,s^2$$

for the case of back-scattering. Because of the abrupt nature of the boundaries, the amount of energy scattered by an ellipsoidal irregularity will depend markedly on its thickness and on the angle of incidence. For an incident wave parallel to the axis of symmetry ($s = 0$) it is possible to show that, for a constant axial ratio, constructive interference occurs for a vertical scale given by

$$b = \tfrac{1}{4}n\lambda\,, \qquad \text{where} \qquad n = 1,2,3,\ldots. \tag{16}$$

As b increases with n, so does the scattering cross section but, unlike the Gaussiau irregularity, the ellipsoidal irregularity has no optimum vertical scale size for maximum back-scattered power. In principle, therefore, it is possible to make b as large as is required to match the observed values of σ. However, it is possible to set an upper limit to the value of b from a close examination of the records of Fraser and Vincent (1970), which show that the vertical extent of the echoes from the moving irregularities is of the same order as the pulse length used ($\sim 3\cdot 75$ km). In order to show no significant broadening of the returned pulse, the irregularities must have possessed a vertical thickness of $\lesssim 2$ km, which would give the ellipsoidal blob a vertical scale of $\lesssim 1$ km, or $\lesssim 8\lambda$ at $2\cdot 4$ MHz. An upper limit on the horizontal scale can be set by examining the way in which the scattered power falls off as the irregularity moves from overhead. Calculations show that sharply bounded ellipsoidal irregularities behave similarly to Gaussian irregularities in this respect and that irregularities with axial ratios of 5 or less return significant amounts of energy for angles less than 10°.

Consequently, the scales of the ellipsoidal irregularities would appear to be limited to vertical and horizontal dimensions of $\sim 5\lambda$ and 25λ respectively, which correspond to a total thickness of 1–$1\cdot 5$ km and an overall diameter of ~ 6–$6\cdot 5$ km. On substituting these values into equation (12) we obtain a scattering coefficient of $\sim 3\ \mathrm{m}^2$ (after allowing for collisions) which is of the right order of magnitude. It is difficult to be more precise about the absolute value of σ owing to the absence of a precise value of ΔN_0 and because of Fresnel zone effects. The radius of the first Fresnel zone at 75 km for frequencies near $2\cdot 5$ MHz is ~ 2 km, which is comparable to the inferred scale of the irregularities. As the horizontal scale changes, it is probable that the scattered power will tend to oscillate about a value which is similar to that for a Fresnel discontinuity. For a change of electron density of $30\ \mathrm{cm}^{-3}$, we have $R_{\mathrm{f}} \approx 10^{-4}$ and $\sigma \approx 10\ \mathrm{m}^2$.

Other models of the variation of density within the irregularities can be visualized. For example, the density might vary in an elliptical fashion given by

$$N = N_0 \exp\big(-\{(x^2+y^2)/a^2+z^2/b^2\}^{\frac{1}{2}}\big). \tag{17}$$

This model does not seem very plausible because it requires discontinuities in the density gradient along the three axes. However, it does have a simple Fourier transform and it is possible to show that the cross section in the high frequency limit is is given by

$$\sigma_0(s) = r_{\mathrm{e}}^2 \Delta N_0^2 |8\pi a^2 b/[1+4k^2\{b^2+(a^2-b^2)s^2\}]|^2 . \tag{18}$$

An analysis similar to that carried out for the ellipsoidal irregularity shows that irregularities which power elliptical variations in density also require horizontal and vertical scales of the order of 20λ and 4λ respectively.

IV. Discussion

In the preceding sections an attempt has been made to deduce from two different sets of observations something about the irregularities responsible for weak scattering from the lower ionosphere. The interpretation of the results suggests that the observations refer to irregularities of different shapes and spatial scales. From the autocorrelation analysis it would appear that the scatterers observed near 95 km often have spatial scales of less or about $\lesssim 100$ m, whereas the class of irregularities observed near 75 km have much larger horizontal and vertical dimensions. However, in order to arrive at these conclusions, certain assumptions were made and these are now critically examined.

It was suggested in Section II that small scale irregularities at heights near 95 km might have a Gaussian distribution of density, but this must depend on how the irregularities are formed. Various modes of formation have been suggested, amongst which are meteors, turbulence, wave motions, and plasma instabilities (Bowhill 1966). It is also possible that different processes might be operative on different occasions. If quasi-coherent wave motions or instabilities (perhaps of the type discussed by Chimonas 1969) are the cause then the type of analysis used here, which requires randomly distributed irregularities, is not applicable. If the source is of a turbulent or meteoric origin then the random medium assumption is realistic, and it is probable that the effects of diffusion would give the irregularities a Gaussian cross section. For example, calculations show that, for a typical eddy diffusion coefficient D of $\sim 100\ \mathrm{m^2\,s^{-1}}$, a point source of electrons diffuses outwards to form a Gaussian irregularity of 30 m scale in only a few seconds. Of course the autocorrelation measurements discussed in Section II show that the irregularities are somewhat anisotropic (axial ratio of about three) which possibly implies that the eddy diffusion acts in an anisotropic manner or that it acts on irregularities which are already anisotropic.

It was shown in Section III that Gaussian irregularities scatter insufficient power to explain the observations at altitudes near 75 km of the solitary drifting reflectors and much larger irregularities with sharp boundaries were invoked. However, this model appears to be somewhat artificial since it relies for much of its efficiency on constructive interference occurring between the front and back surfaces. It becomes more apparent how sharp the boundaries have to be when it is realized that the power reflected from a density gradient one wavelength thick is at least a factor of ten smaller than that reflected from a step discontinuity (see p. 453 of Atlas 1964) . This implies that an ellipsoidal irregularity would require boundaries of thickness $\lesssim \lambda/10$ (that is, $\lesssim 10$ m). Since the irregularities are observed for periods of up to ten minutes it would be necessary for such boundaries to be maintained for at least this length of time. This implies that, if this model is correct, the eddy diffusion coefficient was not large during the observations. In fact, it has been suggested that turbulence occurs only in a sporadic fashion in the mesosphere since the average diffusion coefficient required to maintain the thermal structure of the mesospheric region is $\sim 100\ \mathrm{m^2\,s^{-1}}$ (Hodges 1969). Hodges shows that this average value can probably be supplied by instabilities generated by only a few large scale gravity waves on any given day. Because an eddy diffusion coefficient of $100\ \mathrm{m^2\,s^{-1}}$ would cause a sharp boundary to diffuse through a distance of one wavelength in $\sim$10–20 s, it would appear that the value of D must be significantly less than this for the irregularities to persist over periods of minutes, whatever their shape. For comparison, the recombination time for an irregularity of electron density $\sim 30\ \mathrm{cm^{-3}}$ above the background value is estimated to be $\sim$20–30 min, if a value of $10^{-5}\ \mathrm{cm^3\,s^{-1}}$ is assumed for the effective recombination coefficient at 75 km.

There is other evidence for irregularities with very stable boundaries existing in the D-region. As indicated earlier, both Smith *et al.* (1965) and Fraser and Vincent (1970) report phase path observations of irregularities which maintained a high degree of phase stability over long periods (upwards of half an hour). These irregularities appear to differ from the drifting irregularities under discussion here, in that they have very large horizontal extents and are possibly associated with temperature inversions or dust layers. It is difficult to visualize a mechanism which can generate a sharply bounded irregularity with spatial scales of the order of a kilometre and yet which does not simultaneously generate sufficient turbulence to destroy those boundaries.

The possibility that meteor trails might be responsible for the observations is at first sight attractive because the trails can scatter a significant amount of power over quite large angles. However, meteor trails are normally observed by a specular process and thus the present observations made at vertical incidence would require the trails to be aligned almost horizontally. This means that either the meteors entered the Earth's atmosphere horizontally or that otherwise randomly oriented trails become sufficiently distorted that they become visible. The first possibility would require the meteors to traverse a very long path through the atmosphere, with a great probability of being burnt up before observation, while the second possibility would require large wind shears to distort the trails. Because of these problems it is felt that meteor trails are not a likely explanation although they cannot be entirely ruled out.

V. Conclusions

Measurements of the spatial scales of the diffraction pattern produced by partial reflections from irregularities situated at heights near 95 km show that, when no specular reflections are present, the pattern size is ~ 120 m for an observing frequency of 2 MHz. This pattern size is larger than expected for irregularities which have an isotropic radial distribution of ionization. If the irregularities have a Gaussian distribution then calculations show that the observations can be explained by irregularities whose vertical scales are ~ 30 m and which have horizontal to vertical dimensions in the ratio of about three to one.

Observations of single horizontally-drifting irregularities observed at heights near 75 km are more difficult to explain. Ellipsoidally shaped irregularities whose dimensions are of the order of kilometres can account for the observed characteristics (the amount and angular distribution of the back-scattered power) but it is difficult to conceive how such sharp boundaries can be formed and maintained, although they may not be incompatible with what is known about the dynamics of the mesosphere. If irregularities of this type do exist then only a small number would be required at any one time to explain the average properties of the partial reflections.

It is felt that the observations have not been satisfactorily explained and that further observations are necessary. These observations should preferably be carried out simultaneously at different frequencies and at angles of incidence other than the vertical in order to specify as fully as possible the scattering properties of the irregularities.

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