SOVIET PHYSICS USPEKHI VOLUME 4, NUMBER 1 JULY-AUGUST 1961

RADAR REFLECTIONS FROM AURORAE

B. A. BAGARYATSKII

Usp. Fiz. Nauk **73**, 197-241 (February, 1961)

INTRODUCTION

REFLECTIONS of meter waves from the ionosphere, characteristically related with polar aurora zones, were first observed shortly before the second world war.[1,2] Systematic investigations with use of the much superior radar techniques began only after the war. Contributing to the post-war rediscovery of UHF reflections near the auroral zones was the development of meteoritic radio astronomy service in many countries, since the optimum frequencies of the "auroral"* and meteoritic radio reflections are approximately the same (although the character of the reflected signals is quite different in the two cases).

Radar reflections from aurora have been the subject of considerable attention in geophysics since 1947. Optical methods (spectroscopy and photometry) have made it possible to investigate the excitation processes that take place in the aurorae. The discovered feasibility of radio reflections during the time of aurorae has made it possible to supplement these researches by investigations of the changes in the state of ionization. A study of "auroral radio reflections" is, however, of independent interest. The existence of these reflections demonstrates the presence of certain new features, heretofore unknown, in the polar ionosphere. The connection between the reflections of this type with magnetic disturbances and aurorae is one of the measures of the intense action that corpuscular streams exert on the ionosphere at high latitudes. It is interesting that the use of more sensitive apparatus permits sometimes the detection of radio reflection of the "auroral type" at considerable distances from the auroral zones, and in individual cases even at subtropical latitudes.[3-6] Of special interest is the occurrence of ionization of the "auroral" type during atomic explosions in the upper atmosphere. The high ionization density which results in steady UHF reflections, lasting for tens of minutes, has been observed in this case not only in the explosion zone, but also (after the lapse of a short time) several thousand kilometers away in the magnetically-conjugate point of the opposite hemisphere. This phenomenon is of interest from the point of view of understanding the properties of the earth's radiation belts, apart from the fact that it implies the possibility of obtaining more exact information on the structure of the earth's magnetic field.* An investigation of auroral radio reflections is of great significance for radio communication, particularly in the extensive regions near the auroral zones. Periods during which UHF reflections are observed are frequently characterized by strong absorption of short waves; in some cases the absorption may produce unpleasant static for UHF communication and radar. On the other hand, specific conditions in the ionosphere, which are produced at high latitudes during the time of frequently repeated and prolonged magnetic disturbances, can apparently be used sometimes to effect beyond-the-horizon UHF communication, often under conditions when other bands are utterly or almost utterly unusable.[2,7,8]

Although "radio reflections from aurorae" have been investigated in geophysics for more than ten years, the information accumulated is not always sufficiently well known to specialists of related fields. Thus, for example, we read in the book "Radioastronomy" by Posey and Bracewell, recently translated into Russian (Moscow, IL, 1958): "At high radio frequencies, for example 30 Mc/sec, all or almost all random reflections from the ionospheric levels are due to meteors" (p. 372). This statement is far from true.

The Soviet literature does not include at present any survey or general papers on radar investigations of aurorae. This article is an attempt to present a survey of the data available in the literature and to report the main information on the characteristics of "auroral" radio reflections.

The extensive program of the International Geophysical Year included also investigations of the radio reflections from aurorae. Intensive observations were carried out in many countries.

---

*In connection with the extensive programs of aurora research during the International Geophysical Year, the following terminology, proposed by S. Chapman, has been introduced: the regions of the earth's sphere above 60° northern or southern geomagnetic latitude are called "auroral belts," the regions between 60 and 45° are the "subauroral belts," and the region between the geomagnetic parallels 45° N and 45° is the "minauroral belt." The auroral zones in the narrow sense of the word, i.e., the region where the frequency of appearance of aurorae is a maximum, lie approximately between 65 and 68° geomagnetic latitude. The maxima of these zones are shifted appreciably towards the lower lattitudes during the time of geomagnetic disturbances. The term "auroral disturbances," which has recently come into use to denote the aggregate of the processes that take place in the auroral zones during the times of disturbances, is convenient because of its brevity, and we believe it quite usable. The term "auroral reflections" is convenient in this case to denote the type of reflection from the ionsphere which is characteristic for the auroral zones during the periods of "auroral disturbances;" this term is perhaps generally preferable to the presently used phrase "radio reflections from aurorae," which essentially is physically incorrect.

*Concerning artificial ionization, see the series of articles in J. Geophys. Research No. 8, 64 (1959). These problems are not discussed in the present article.

During the time of the International Geophysical Year, and during the preparations for it, the Soviet geophysicists have also carried out many observations, some of considerable interest.* The materials published up to the middle of 1960 are essentially covered by this review, but it must be recognized that the processing and publication of the greater part of the results of the IGY is not yet concluded, and is therefore not included in this review.

1. PRINCIPAL CHARACTERISTICS OF THE PHENOMENON

The term "radio reflections from aurorae" is not physically accurate and is convenient only because of its relative brevity: the aurora, being an optical object, cannot reflect radio waves. By force of tradition, we can apparently continue to use this term with the qualification that by reflections "from aurorae" we mean reflections from the regions of increased ionization associated with the aurorae.

It is known from many years' ionospheric sounding,[9] from observations with artificial satellites,[10,11] and from direct rocket measurements[12,13] that under normal conditions the maximum electron density in the ionosphere does not exceed several times $10^6/\text{cm}^3$. This daytime maximum value occurs at a height of 300 – 350 km in the F_2 layer. In the F_1 layer, which exists only during the daytime, the concentration is one order of magnitude less. At heights of 100 – 120 km in the E region the normal electron concentration under daytime conditions is approximately $1.5 \times 10^5/\text{cm}^3$. It decreases appreciably during the night. The D layer is not always present and its electron density is not greater than $(5 - 8) \times 10^3/\text{cm}^3$.

Recent research has shown[10-13] that the subdivision of the ionosphere into distinct layers does not correspond to reality: the increase in the electron concentration towards the maximum in the F_2 layer (glossing over details) is more or less monotonic. To some extent, however, the subdivision into the E, F_1, and F_2 regions remains valid, since it does apparently mirror the real existence in the ionosphere of layers with different physical conditions, characterized for example by a different ionizing agent or by a different main ionized component.

Figure 1 shows the distribution of the electron concentration from 100 km up to the outer region of the ionosphere, based on the data of Ya. L. Al'pert et al.[10] (determined by radio signals from the first Soviet satellite), K. I. Gringauz (measurement of the electron concentration with a geophysical rocket) and of Schmelovsky et al. (East Germany) (observations of the signals from the third Soviet satellite).[11]

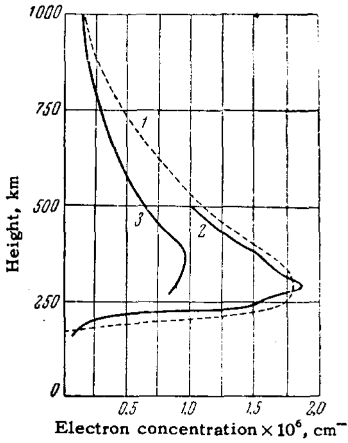


FIG. 1. Distribution of electron concentration in height. 1 – from observations with the first Soviet satellite in 1957 (Ya. L. Al'pert, F. F. Dobryakova, É. F. Chudesenko, B. S. Shapiro); 2 – from rocket measurements, 1958 (K. I. Gringauz); 3 – from observations with the third Soviet satellite, 1958-1959 (K. Schmelovsky, L. Klinker, R. Schmitt).

If we use the connection between the critical frequency f_{cr} of the regular reflection from the ionosphere and the electron concentration N_m at the maximum of the layer

$$N_m = 1.24 \cdot 10^4 f_{cr}^2 \qquad (1)$$

(the critical frequency is in Mc), then the critical frequencies in the region of the absolute maximum of the concentration should not exceed 10 or 15 Mc/sec ($\lambda_{cr} \cong 30 - 20$ m). For reflection from the normal E layer, they amount to 3 – 5 Mc/sec ($\lambda_{cr} = 100 - 60$ m), and as a rule they do not exceed 7 – 8 Mc/sec in reflection from the E_s sporadic layers.

It was noted first in 1940, and firmly established after 1947, that reflections from a certain part of the ionosphere near the auroral zones can occur at much higher frequencies, on the order of 30 Mc and higher, up to 1000 Mc.

If it is assumed that Eq. (1) can be used for reflections at meter and decimeter frequencies in the auroral zones on the basis by which it is applied to reflections from the regular ionospheric layers, this means that the electron concentration in the reflecting regions of the aurorae should exceed $10^7/\text{cm}^3$ for reflected 30-Mc signals and $10^8/\text{cm}^3$ at 100 Mc and above. Is such a concentration of electrons actually produced in the ionosphere during the aurorae? To answer this question we must obviously have some data on the mechanism of the "auroral" reflections. We can assume a priori at least four possible mechanisms: a) total reflection from a regular surface bounding the ionization region, in which the maximum electron concentration exceeds the critical value for the given wavelength and the thickness of the transition layer is much greater than the wavelength; b) partial (Fresnel) reflection from a sufficiently distinct interface, behind which is an ionization region with an electron concentration below critical value (when the transition layer thickness amounts to several wavelengths the character of the reflection remains the same, but it is less than the

---

*Special recognition should be given to the services of Ya. G. Birfel'd for the organization of the IGY radio research on aurorae in the Soviet Union.

Fresnel value); c) reflection from a narrow more or less "symmetrical" layer, in which the electron concentration exceeds the critical value; the reflection is incomplete because the wave energy penetrates through the layer; d) scattering or incoherent reflection from random ionization inhomogeneities, the dimensions, shapes, and electron concentrations of which can vary in different manners.

The use of Eq. (1) to estimate the electron concentration corresponds to the first type of reflection, i.e., to the "classical" case of reflection from regular ionospheric layers. The reflecting object should have dimensions not smaller than the diameter of the first Fresnel zone. In view of the conditions prevailing in radar reflections (the transmitter and receiver antennas are either combined or located close to each other), the reflecting surface must be assumed to be normal to the radar beam. Since the diameter of the Fresnel zone for a wavelength of about four meters and a distance on the order of 300 km (minimum distance for ordinary radar reflections from aurorae) is approximately 1 km, this should also be the minimum diameter of the ionization region, in which the average electron concentration is on the order of $10^7 - 10^8$ electrons/cm^3. From the point of view of information obtained on aurorae, by optical observations, there are no objections at all to assuming such dimensions for the ionization regions. Actually, both horizontal and vertical dimensions of the arcs and curtains of the aurorae, let alone the diffuse formations, are considerably greater than 1 km. The depths of the aurorae apparently reach hundreds of meters, and perhaps more. In contradiction with these ideas regarding the structure of the ionizing reflecting regions and the mechanism of reflection is the estimated intensity of the reflected signals. Even the results of the first observations[14] have shown[15] that the power of the received signals is much less (40 — 60 db) than called for by the simple interpretation just described. Obviously the assumption that the phenomenon that takes place in "auroral" reflections is analogous to ordinary reflection from ionospheric layers (but at considerably higher frequencies) does not agree with the main results of the observations.

A further choice between the reflection mechanisms is much more difficult to make. Although the mechanism of the reflection and the main physical characteristics of the reflecting formations remain the central questions in the entire problem and are discussed in one form or another in almost all the works devoted to radio reflections from aurorae, there is as yet no unequivocal reflection mechanism responsible for the main features of the radio echo from the aurorae.

The gist of the difficulties in the interpretation of the observed data will become clear once the materials themselves are described. But before we start on this main section of the article, we should report some data on the experimental tools used in the research.

The first observed auroral radio echoes were registered using the radar techniques of meteoritic astronomy. In the special radar stations organized in various countries for the observation of aurorae, the work was carried out usually with standard radars which were only slightly modified. Apparatus specialized for definite problems came into use somewhat later, but most published results pertain to work done with the simplest radar techniques.

By virtue of the relative stability of radio reflections from aurorae (compared with meteor reflections), the use of directional moving antennas is not only feasible, but also extremely desirable.

In most stations the antennas can be rotated only about the vertical axis, but horizontal rotation is provided in some cases. It must be pointed out that for a fixed beamwidth the probability of reception of reflections from aurorae, being directly proportional to the energy radiated, depends on the power and on the duration of the pulse.

Table I contains the main parameters of radars customarily used for the investigation of aurorae (based on materials in references 14, 16, 17 — 19, 21, 22, 24, 26, 30, 34, 42, and 71).

Table I. Characteristics of radars used for the investigation of polar aurorae

Frequencies used	from 30 Mc upward (to 1000 Mc)
Types of antennas.	wave channel, parabolic
Antenna gain	from 4–5 to 270
Transmitter power.	from 5 to 100 kw (most frequently 50–75 kw)
Receiver sensitivity.	from 10^{-12} to 10^{-16} w
Duration of sounding pulse . . .	from 8 to 500 μsec
Pulse repetition frequency . . .	25–60 cps
Types of display	amplitude, intensity, and circular

The first post-war report on radio reflections due to aurorae is that of Lovell, Clegg, and Ellyett.[14] Inasmuch as the description of the phenomenon as given by these authors is quite typical of many later investigations, we cite their principal facts. The equipment was located in southern England, in the region of the Jodrell Bank Radioastronomical Observatory, and was principally designed for the investigation of meteors. The work was carried out simultaneously at 46 and 72 Mc. The radar antennas had a weak directivity (the gain relative to a half-wave dipole was 4). The principal lobe of the radiation pattern was oriented toward the zenith. The reflected signals, observed at night between the 15th and 16th of August 1947, were of long duration. The 46-Mc signal stayed on the radar screen for a half hour; at 72 Mc, however, the reflections existed for only a part of this time. At either frequency, the reflections maintained approximately a constant range, on the order of 450 — 480 km, although a certain part of the time the range of the reflections extended to 600 — 700 km.

Simultaneously with the radio reflections, the aurorae were observed visually. Near the northern horizon they were in the form of light columns for several hours prior to the appearance of the radio reflections; the appearance of the glowing cloud in the zenith of the Jodrell Bank station coincided with the start of the radio echo. The reflections ceased approximately simultaneously with the breakup of the cloud into individual bands. Lovell, Clegg, and Ellyett concluded from this that they observed stable reflections (at 46 Mc) from the region of increased ionization, which coincided with the cloud-like aurorae in the zenith. The authors have proposed that the ionization on the cloud was above critical for 46 Mc ($N_m > 2.6 \times 10^7/\text{cm}^3$) although it probably did not exceed $6.5 \times 10^7/\text{cm}^3$, and that the reflection range (~480 km) characterized the actual height of the aurora.

As became clear after several subsequent investigations, these conclusions were in error. All the later observations, performed with antennas with narrower beams, showed that the zenith region is as a rule not responsible for the formation of the reflections during the aurorae. Further, the 480-km glow is admittedly exceedingly high for an aurora of the type observed by Lovell et al. Finally, as was first pointed out by Herlofson,[15] the hypothesis of total reflection from an ionized cloud cannot be reconciled with estimated intensities of the reflected signals.

Omitting the description of many later experiments,[16–24] let us outline the main features of the phenomenon of radio reflections from aurorae, as viewed at the present time.

a. Reflection Range

The reflected signals arrive as a rule from distances of 300 — 700 km and more. Although the aurora observed simultaneously with the reflection may develop in the observer's zenith, and consequently the distance to its lower boundary can hardly be greater than 100 or 150 km in this case, no reflections are observed at these ranges. The exceptions to this rule are rare.

Mentions of such exceptions are found in the paper by McKinley and Millman[25] (Ottawa), who observed the constant presence of weak reflections at 33 Mc at ranges 80 — 90 km, and in the paper by Birfel'd,[8] who observed near Murmansk reflections at ranges of 150 km upward.

b. Types of Reflections

The reflected groups of signals frequently fill on the radar screen a range interval of several kilometers; such signal groups are called "diffuse reflections"; these are in contrast with signals consisting of single pulses, called "discrete reflections."

Figure 2 shows examples of certain types of reflections.[26,27]

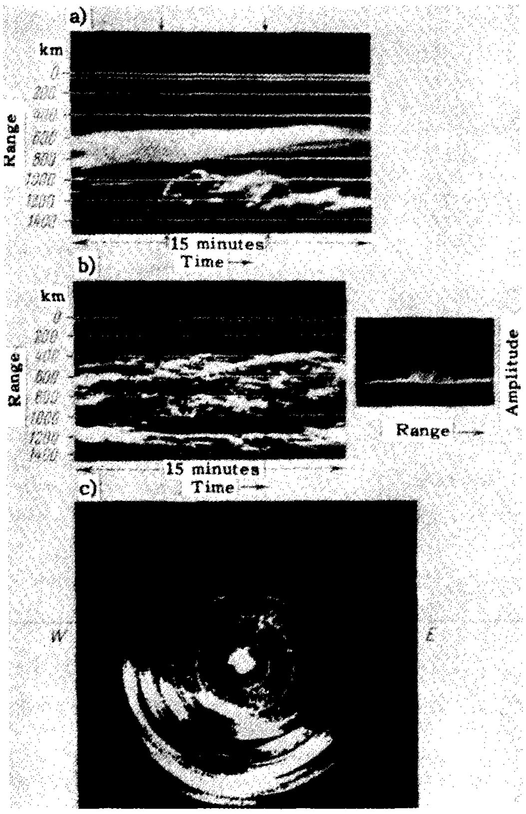


FIG. 2. Examples of registration of radio reflections from aurorae.[26,27] a) Record of intensity display signals on a continuously moving film. Main signal – diffuse without structure. b) Left – the same as in (a), but the diffuse signal has a structure. Individual discrete signals are seen. Right – signal on the amplitude display. c) Signals as seen on a circular display. The recording was made in the southern hemisphere, and therefore the region of reflection lies to the south of the station.

c. Character of Connection with the Aurorae

Although the visual aurorae and radio reflections are definitely correlated with each other within long time intervals, there is no detailed correlation in their time variation. The varying intensity of the radio reflection can for the most part not be related with the successive development of the optical picture of the aurora. This fact, stated qualitatively by most observers, was subjected to a convincing statistical verification by Gadsden.[28]

Table II, taken from the article by Lyon,[29] gives an idea of the connection between the observed forms of the aurorae and the radar reflections. The numbers in the second, third, and fourth columns denote the number of ten-minute intervals during which the observers noted one of the two phenomena.

d. Duration of Reflections

The average lifetime of the reflected signal on the radar screen ranges from minutes to several times ten minutes. As indicated by Ya. G. Birfel'd,[24] signals

Table II. Correlation between the radio echo and visual forms of aurorae (after Lyon[29])

Forms of the aurorae	Visual	Radio echo	No radio echo	Percent of visual forms yielding a radio echo
Uniform arcs	365	18	347	5
Complex arcs and strips	174	54	120	31
Ray patterns . .	371	52	319	14
No aurorae	–	4	-	—
Total . .	910	124	786	14

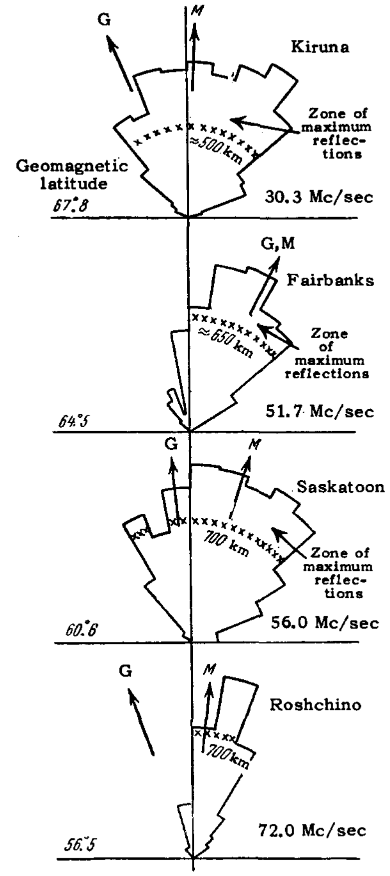


FIG. 3. Polar diagram showing the mean azimuthal distribution of reflected signals for different stations (from data of references 18, 30, and 32).

of the diffuse type remain steady sometimes for many hours. During that time the signals may change their form (for example, the form of the envelope on the "range-amplitude" display), intensity, extent, and range, but do not vanish from the screen. In other cases the lifetime of the signal is measured in seconds (these are usually the discrete signals); sometimes a relatively rapid vanishing of signals at some ranges and their appearance at neighboring ranges may be observed.[8,24]

e. Location of the Reflection Regions in Space

For stations of the northern hemisphere, the regions from which the reflections come are statistically located predominantly in the northern quadrant relative to the station. The picture is independent of whether the observation station has a lower or higher latitude than the auroral zone, or whether it is located in the zone itself. The prevalent opinion was at first that the reflection regions are symmetrical about the geomagnetic meridians of the corresponding stations, but this is apparently untrue. The most recent observations[27,30,31] point more readily to a connection between the symmetry of the reflecting regions and the local magnetic fields in the vicinity of each station, i.e., a connection with the direction of the magnetic declination. Figure 3 shows averaged data for several stations. The arrow G points to the geomagnetic pole, while M is in the direction of the magnetic declination near the corresponding stations; the reflection zones are seen to be grouped about the latter directions.

f. Aspect Sensitivity of Reflections

In observations at medium-latitude stations, such as Jodrell Bank, Oslo, Saskatoon, Roshchino (Leningrad), and others the radio reflections from the aurorae do not appear at elevation angles greater than 10 — 12° above the horizon. This could have been attributed to the fact that aurorae are in general not observed high above the horizon at medium latitudes. An unexpected fact, however, is that in stations located in the auroral zones or in the direct vicinity of these zones, such as Tromsoe, Kiruna, Fairbanks, Loparskaya (Murmansk), and others the reflections are practically never at large angles to the horizon, independently of the intensity of the visual forms of the aurorae observed during the time of reflection near the observer's zenith.* The absence of reflections at large angles to the horizon was thoroughly investigated by Harang and Landmark[22] at 35 and 74 Mc, and by Currie, Forsyth, and Vawter in Saskatoon at 56 and 106.5 Mc. The antenna direction could be varied in the vertical plane from 0 to 45° (up to 90° in the case of 106.5 Mc), so as to follow the bright visual forms of the aurorae. In either case, the limiting elevation angle for the reception of reflections was approximately 15°.

The aggregate of the azimuthal features of the reflections from aurorae, as well as those connected with the elevation angle, observed when working with a directional beam, has been named the "aspect sensitivity of reflections."

g. Identification of Reflecting Regions with Visual Singularities of the Structures of Aurorae

Reports by various authors concerning this matter are quite contradictory. In the earliest observations[17,18] the authors attempted to establish a clear cut connec-

---

*Ya. G. Birfel'd reports[8] isolated reception of zenith reflections in Loparskaya, near Murmansk.

tion between the arrival of reflections and the appearance of bright forms of aurorae at the corresponding points of the sky. The predominant role of ray-like forms was sometimes emphasized.[19,32] The majority of the later investigations, however, indicate that there is apparently no direct connection between the reflecting regions and any characteristic structural features of the visual forms of the aurorae.[20,22,29,33,34] It must be recognized that in the case of ranges on the order of 600 — 800 km, which are characteristic of radio reflections from aurorae, the latter should be low above the horizon, where the details are no longer easy to discern.

h. Height of Reflections

In the investigation of aurorae by optical methods, a rather difficult and yet important problem is the determination of the absolute height of the aurora. Many optical measurements of the heights of aurorae by the method of parallactic photography have been carried out by Stormer and his co-workers in Norway.[35] However, modern photoelectric methods of photometry of polar aurorae call for rapid determinations of the height of the glow. It was assumed first that radar could solve this problem This has not yet been accomplished, and unfortunately it must be admitted that it is generally impossible to do so with modern methods, for reasons indicated in items c and g (absence of strict correlation between the visible forms of the aurorae and the radio reflections).

The heights of the reflecting formations themselves can naturally be determined more or less accurately from the slant range and the elevation angle of the reflections. To increase the accuracy, antennas with multiple-lobe directivity patterns are used. Currie, Forsyth, and Vawter,[19] after carrying out a rather tedious calculation of the corrections for refraction and the dependence of the frequency of occurrence of the glows on the geomagnetic latitude, obtained for the average altitude of the reflecting layer a figure close to 110 km. V. N. Dovger,[36] using a two-lobe scanning antenna ("wave channel"), obtained for the altitudes of the reflecting formations values from 80 to 160 km, each measurement having an accuracy of ± 5 km.

Unwin and Gadsden[26,37] used in New Zealand an antenna having up to 21 lobes. In most cases the reflected signals, due to individual lobes, were superimposed, forming a discrete or diffuse reflection of the type shown in Fig. 2. However, in the case of one type of diffuse reflections, the signals from all the lobes were received separately, and consequently were distributed over a large portion of the range scale (Fig. 4). Apparently the depth of "stacking" of the reflecting or scattering inhomogeneity, which form in their totality a certain reflecting layer. was in this case sufficiently small (not more than 2.5 km). The average height of the layer was found to be, according to Unwin and Gadsden, 110.9 ± 3.1 km, and as the range increased from 400 to 1200 km the heights of the layer did not vary by more than several kilometers.

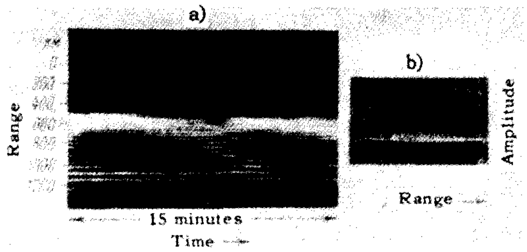


FIG. 4. Reflections from an extended thin layer, received by a multiple-lobe antenna (Unwin and Gadsden[26,27]). a) Recording of the intensity display on the moving film; b) pattern on the amplitude display.

The measurements described, along with certain other less accurate estimates, make it possible to consider it more or less established now that the main zone forming the "auroral" radar reflections, is the region of the ionosphere locating closely at the altitude of the E layer and the lower limit of the polar aurorae, i.e., approximately between 90 and 120 km.

2. DAILY VARIATION OF THE RADIO REFLECTIONS AND THEIR CORRELATION WITH GEOMAGNETIC ACTIVITY

The aggregate of the results indicated in the preceding section, produces a pattern of rather stringent conditions that must be satisfied if reflections are to be registered. An explanation of the selectivity of the reflections, proposed on the basis of the analogy with reflection from meteor trails,[15] lies in an assumption that the reflecting formations are anisotropic. The symmetry of the reflecting regions about the magnetic field leads to the additional conclusion that the structure of the ionized regions, responsible for the radio reflections during the polar aurorae, is connected with the structure of the earth's magnetic field. This explanation, first advanced by Herlogson,[15] was developed by Chapman in detail.[38] The scheme which he proposes for the geometrical reflection conditions will be discussed later on (Sec. 4).

The connection between the "geometry" of the auroral ionization and the magnetic field leads us to expect the presence of correlation between the magnetic disturbances and the parameters that characterize the radio reflections.

Notice should first be taken of the far reaching parallelism between the mean daily course of the magnetic disturbances in polar regions and the probability of appearance of radio reflections. Figure 5, taken from the paper by A. P. Nikol'skii,[39] shows the dependence of the number of bay disturbances of medium and large force for the Bukhta Tikhaya station over the period from 1933 — 1946, on the time of the day. Later data by M. S. Bobrov,[40] who used materials

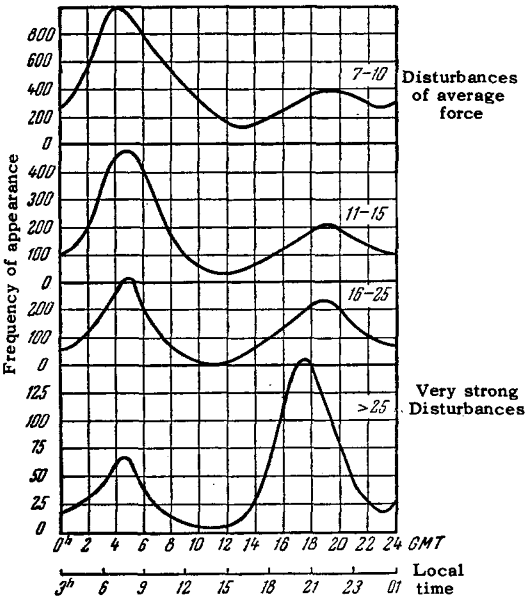


FIG. 5. Daily course of the magnetic disturbances at the Bukhta Tikhaya station (after A. P. Nikol'skiĭ[39]). (Numbers – degree of disturbance in arbitrary balls.)

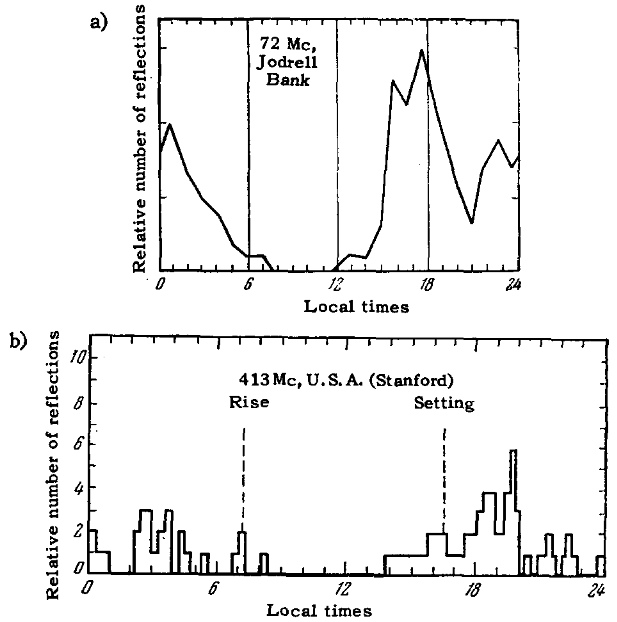


FIG. 7. a) Daily course of radio reflections on 72 Mc at Jodrell Bank (after T. D. Kaiser[41]). b) Daily course of radio reflections on 413 Mc at Stanford (Fricker et al.[43]).

from magnetic stations practically all over the earth (IGY data), also show that in regions adjacent to the auroral zones the global magnetic disturbances are no longer in phase as they are in the medium and equatorial latitudes, and that most disturbances near the auroral zones take place at night.

Figures 6, 7a, and 7b illustrate the statistics of the appearance of radio reflections for certain stations in the eastern and western hemispheres.[41-43] A sharp decrease in the number of bay disturbances takes place near local noon time, when as a rule there are practically no radio reflections.* A detailed statistical analysis of the time of occurrence of magnetic disturbances for a large number of polar stations, located at different longitudes and latitudes, and carried out by A. P. Nikol'skii, has disclosed that the daily course of the magnetic storms has specific peculiarities that are unique to individual arctic stations. Depending on the geomagnetic coordinates, a change takes place in both the number of maxima (from one to three) and in the time of their occurrence. The average number of radio reflections, according to the data of Ya. G. Birfel'd,[44] is in many cases closely related with these peculiarities of the daily variation of the magnetic disturbances.

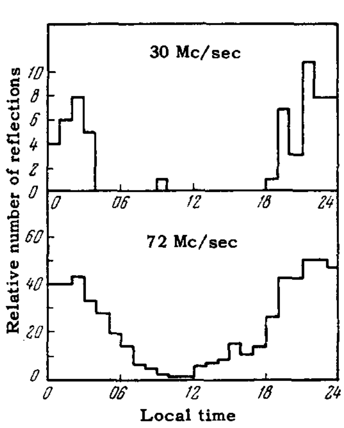


FIG. 6. Daily course of radio reflections at 30 and 72 Mc in the Loparskaya station (after A. I. Grachev[42]).

The absolute magnitudes and signs of the bay disturbances influence quite significantly the probability of the appearance of radio reflections. Meek and McNamara[45] investigated the connection between the appearance of radio reflections and the magnetic disturbances for the Saskatoon station (frequencies 56 and 106.5 Mc). They found that positive magnetic bays are accompanied by a regular intensification of radio reflections, but negative bays do not give such an effect.

Bullough and Kaiser and their co-workers (Jodrell Bank),[21,41,46] V. I. Pogorelov (Roshchino Station near Leningrad),[47] V. I. Yarin (Yakutsk),[48] and Gadsden (New Zealand)[49] have compared the probability of appearance of auroral radio reflections with the absolute magnitudes of the magnetic disturbances. In all cases it is found reliably that the probability of appearance of reflections increases appreciably in large magnetic disturbances. In Jodrell Bank, 92% of the integral duration of the echo occurs when $|\Delta Z| > 50\gamma$; in Roshchino, which has a higher geomagnetic latitude, the number of echos for $|\Delta X| > 500\gamma$ is about 70% of the total number of cases, and not more than 30% when $|\Delta X| < 500\gamma$. The sign of the magnetic disturbance "preferred" by the radio reflections is different in these two stations: in Roshchino positive bay disturbances are practically never accompanied by radio reflections, whereas in Jodrell Bank the probability of appearance of reflections is approximately twice

---

*The question of daytime reflections is considered in Sec. 3.

as large during positive bays as during negative ones.

For the Yakutsk Station, as was shown by V. I. Yarin[48] with a rather large amount of statistical material, the radio reflections on 72 Mc are in correlation over the greater part of the day with negative magnetic disturbances (from the level of the quiescent field) and only at night do they correlate with the positive ones.

The curves of Fig. 8 show the average connection between the local K index of the magnetic activity and the probability of radio reflections on 55 Mc, obtained by Gadsden[49] in investigations in New Zealand. (The point of observation had a geomagnetic latitude 51.5° S; the values of the K index were taken for the Maccouri Island, the latitude of which is close to the assumed latitude of the reflection region.) An analogous connection was obtained in Ottawa on 50 Mc by Bhattacharyya.[50] The latter, however, did not observe any difference in the appearance of the reflections for positive and negative bays. The probability of occurrence of reflections was equally high in either case (82 – 86%) Bhattacharyya also noted a systematic delay of several minutes in the instant of occurrence of the maximum of the magnetic disturbance, relative to the maximum of the intensity of reflections.

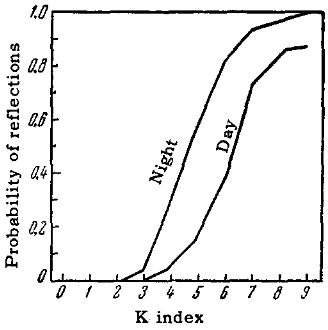


FIG. 8. Connection between the probability of radio reflections and the K index of the magnetic activity (after Gadsden[4]).

The selectivity of the radio reflections with respect to the sign of the magnetic disturbances, is connected, according to certain assumptions,[45,50] with the fact that in the case of negative bays the ionization and the ionosphere currents are localized in lower latitudes than in the case of positive disturbances. For high-latitude radar stations this should lead to a disappearance of the reflections from the northern (predominant) direction, whereas for medium-latitude points this should evidently be less appreciable.

By way of illustration of the parallelism between the intensity of the radio reflections and the magnetic storms, we give one of the magnetograms of Bullough, Davidson, Kaiser, and Watkins,[46] on which the variation of the intensity and the direction of the drift of the front of reflections coincide with the course of the magnetic disturbance (Fig. 9). As can be seen from this figure, reflections at Jodrell Bank correlate with bays of both signs, but the direction of the drift of the reflections changes together with the sign of the bay. This circumstance agrees with the interpretation of Bhattacharyya, given above.[50]

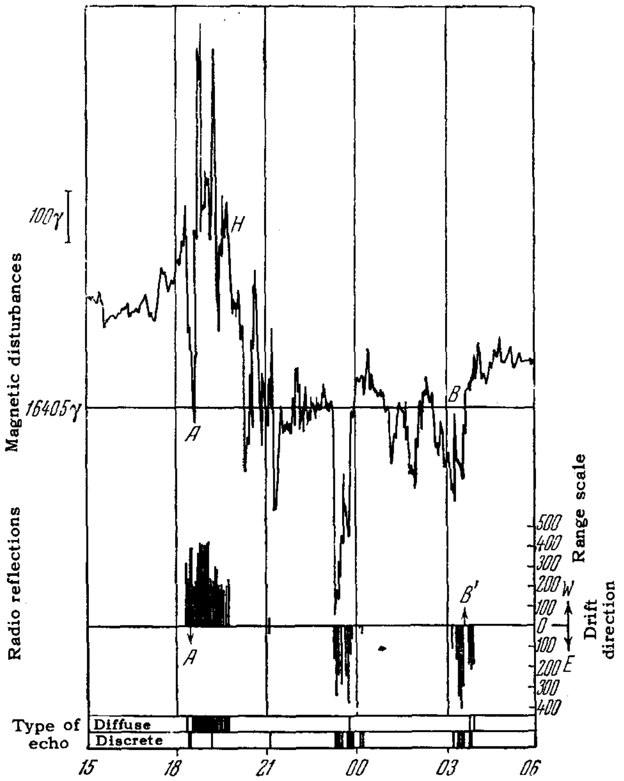


FIG. 9. Recording of magnetic disturbance (top) and a diagram showing the range, the drift direction, and the type of simultaneous echo signals (below); after Bullough et al.[46] The abscissas are in world time.

Observations of radio reflections in the Antarctic were started for the first time in 1957. Figure 10, published by Harrison and Watkins,[51] shows the distribution by days of the number of hours of reception of reflections at the Holly Bay station (geographic coordinates 75.5° S and 26.6° W) for the six months during which this station was in operation (upper diagram). Shown underneath is the distribution of the daily sums of the planetary K index (K_p) and a diagram of reflections received during the same period at Jodrell Bank. What is striking is the almost complete agreement between the first two diagrams: the number of hours during which it becomes possible to observe radio reflections on a specific day is proportional to the degree of magnetic disturbance for that day. The lower diagram of Fig. 10 points to a similar regularity for the Jodrell Bank station, although, owing to the medium latitude of this station, the probability of receiving radio reflections is considerably less there than in Holly Bay.

In 1959 the Soviet researchers B. E. Bryunelli and S. M. Sandulenko carried out radar observations of aurorae at the Mirnyĭ station.[31] The radar operated on 72 Mc and had a pulse power of 75 kw. Mirnyĭ is located in the southern zone of the polar aurorae, and

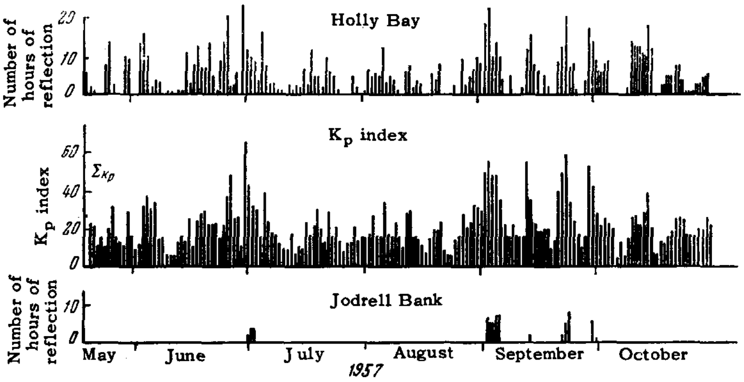


FIG. 10. Comparison of the change in the number of radio reflections with change in magnetic activity (after Harrison and Watkins[51]). Top – radio reflections (number of hours during the day) in the Holly-Bay station, bottom – the same at Jodrell Bank. Center – daily sums of the planetary K index.

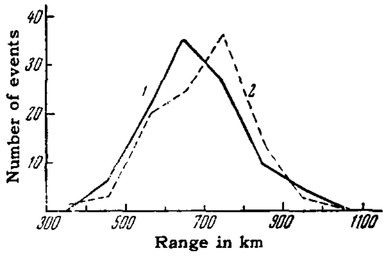


FIG. 11. Distribution of average ranges of radio reflections at the Mirnyĭ Station (after Bryunelli and Sandulenko[31]).
1 – March and May
2 – April 1959.

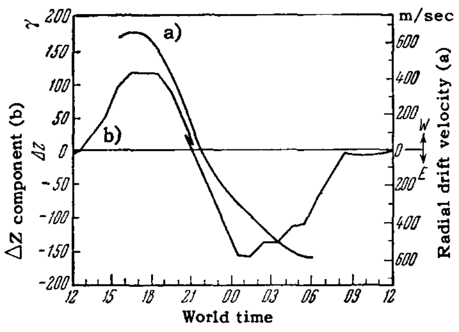


FIG. 12. Radial velocity of the drift of radio reflections (a) and the variation of the Z component of the magnetic field (b) (after Kaiser[41]).

the plane of the magnetic meridian passes through the station in an east-west direction. The maximum number of radio reflections is observed from the east, i.e., from the direction of the magnetic pole, in good agreement with the reflection perpendicularity requirement (see Sec. 4) if the effective field at heights of about 100 km is assumed to be the local and not the geomagnetic field. The distribution of the reflection ranges in Mirnyĭ is shown in Fig. 11. According to the calculations of Bryunelli and Sandulenko, the heights of the reflection points that satisfy the perpendicularity requirement are less than 80 km for all ranges (to the east of the station), with the exception of the distance ~ 600 km. Connected with the fact, in the author's opinion, is also the position of the maximum at 600 – 800 km. The calculations were made, however, with allowance for the variation in the magnetic declination with height, which in the case of the local field is apparently not quite true; actually the true height may be close to 100 km, if it is assumed that the declination is 1.5° less than assumed in the calculations.

The results of the radio observations lead also to the conclusion that there is a statistical correlation between the auroral radio reflections and the daily variations of the earth's unperturbed magnetic field. One of the readily recordable parameters is the average velocity of displacement of the reflecting formations relative to the observer. The displacement of the signals can be readily seen on the amplitude display screen.[24] It is even more convenient to measure the displacement of the reflection front by photographing the intensity display screen on a continuously moving film. Bullough and Kaiser and their co-workers[41] at Jodrell Bank, in an analysis of the statistics of the variation of the radial velocity components of the signal front, established the regularity shown in Fig. 12. The reflecting formation moves away from the observer during evening hours (local time), stops at about 21 hours (during that time the number of reflections is a minimum), after which it reverses direction. The average velocities of the reflection front reach a maximum at approximately 16 hours (+600 m/sec) and at 03 – 06 hours (–600 m/sec). No reflections are observed from 06 to 15 hours. The variation of the velocity of the signal front is in correlation with the daily course of the vertical component (Z component) of the magnetic field near the reflection region (curve b of Fig. 12). The variation ΔZ also vanishes and reverses sign at about 21 hours local time. On this basis, Bullough and Kaiser interpret the radial velocities measured by the radar as being the projections of the east-west motion of the ionized formations along the line of the geomagnetic latitude.

V. I. Pogorelov[52] observed at the Roshchino station (near Leningrad) another statistical regularity, namely the correlation of the average reflection range with the variations of the quiescent magnetic field. Figure 13 shows the daily variation of the ranges of the reflections received in Roshchino and the course of the simultaneous variation of the horizontal component of the magnetic field in a zone close to the reflection region. In the author's opinion, the change in reflection range can be interpreted as a direct result of the variation of the inclination of the magnetic lines to the earth's surface in the region from which the reflections arrive. This in turn causes a shift of the

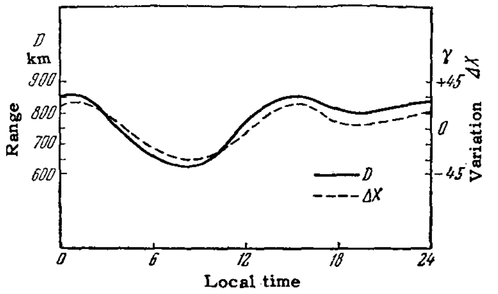


FIG. 13. Correlation between the average range of reflections with the variations of the magnetic field (X component) (after Pogorelov[52]).

points that satisfy the perpendicularity requirement.

Certain optical observations demonstrate quite clearly the real possibility of local changes in the curvature of the magnetic lines during the time of polar aurorae. Thus, for example, Abbot[53] observed during the development of the corona (zenith form of the polar aurora) a displacement of the radiant point by an amount up to 7.5°, although during the same time the main magnetic elements, measured on the earth's surface, remained practically unchanged.

In addition to the direct and close correlation with magnetic disturbances (and the periodic variations), one can apparently assert that a definite correlation exists between the radio reflections and the solar activity. The existence of such a relation was indicated by Ya. G. Birfel'd,[8] who concluded, by comparing the results of observations over approximately five years (1954 — 1959), that the number and intensity of the radio reflections increase as the maximum of solar activity draws nearer. Obviously this tendency is in full agreement with the regularity established long ago for magnetic disturbances and polar aurorae.

Thus, the observational material which is amenable to analysis enables us to state that an undisputed correlation exists between the magnetic disturbances and the appearance of the polar-ionosphere anomalies that are manifest by the presence of "auroral" radio reflections. It can be assumed that the penetration of corpuscular streams causes the ionosphere in the zone of the polar aurorae and near the pole to acquire many new properties, which are lacking in the quieter periods and which are not noted at other latitudes.

3. CONNECTION BETWEEN RADIO REFLECTIONS AND CERTAIN FEATURES OF THE SPORADIC IONIZATION NEAR THE AURORAL ZONES

Along with the existence of "auroral" radio reflections, the polar ionosphere is characterized also by other anomalies. These include the increased intensity of the sporadic ionization of the E_S, E_{2S}, and F_S type, anomalous absorption, and others.

A detailed analysis of the sporadic ionization is outside the scope of the present article, but a brief review of the regularities of E_S ionization observed in the high-latitude regions is useful, in view of its definite correlation with the radio reflections.

The sporadic ionization in polar regions is much more intense than in any other region.[54-56] The sporadic layers at heights from 100 to 150 km occur more frequently there and exist on the average for a longer time. It can be regarded as established that the course of the intensity of the E_S ionization at high latitudes is controlled by the geomagnetic time. Among the first to call attention to this was V. M. Driatskii,[55] who showed that the maximum of the E_S ionization, according to data from arctic stations in the eastern hemisphere, coincides approximately with geomagnetic midnight. Penndorf and Coroniti obtained the same result for the western hemisphere, and pointed out that it is valid only for stations lying farther north than the auroral zone. The maximum of the E_S ionization for stations lying in the zone of the polar aurorae corresponds as a rule to a time before local midnight, and the spread reaches ±2 — 3 hours for individual stations.

Like the "auroral" radio reflections at UHF, the sporadic E_S formations in the zone of polar aurorae are practically never observed in the daytime. This pertains, according to Penndorf and Coroniti,[56] equally well to E_S reflections with limiting frequencies $f_{E_S} > 5$ Mc and $f_{E_S} > 7$ Mc. This behavior of the E_S ionization was confirmed by other observers. Ya. I. Fel'dshteĭn, carrying out observations on the Dixon Island, indicated that the nighttime E_S layers (which he denotes as E_N) usually vanish completely in the daytime even during strong magnetic disturbances.

An analogous daily course of occurrence of E_S reflections in Murmansk was observed for several years by R. A. Zevakina and Z. Ts. Rappoport.[54] According to these authors, the probability of appearance of E_S during nighttime reaches 90%, while the maximum of the E_S reflections coincides with local midnight.

Interesting data, based on the processing of observations made at the SP-3 station (1954 — 1955), have been communicated by V. M. Driatskii and A. S. Besprozvannaya.[55] The SP-3 station drifted inside the polar auroral zone; for part of the time it was in the direct vicinity of the geographic pole. The average magnetic disturbance in the pole region was much lower than in the zone of polar aurorae during the same period (Tiksi Bay, Dixon Island).

There was no constant E layer at all during the winter months, when the sun was less than 10.5° under the horizon. The sporadic E_S layer (and also the somewhat higher E_{2S} layer) was observed during all seasons of the year, although limiting frequencies $f_{E_S} > 7$ Mc were measured much more rarely than $f_{E_S} > 3$ Mc. The averaged data suggest a correlation between the daily course of the magnetic disturbance (r_H^γ) and the behavior of E_S, namely an increase in f_{E_S} corresponds to an increase in magnetic activity. Apparently no fixed time of the maximum, such as occurs at lower latitudes, was observed in the SP-3 station. This may be due either to the displacement of the station or to its position inside the auroral zone. The E_s reflections occurred at the SP-3 station most frequently during morning hours (local time).

Thus, the character of the distribution of the sporadic E_s reflections in time near the auroral zone and to the north of this zone differ radically from the daily course of the E_s reflections in the southern latitudes (see, for example, reference 58), where the maximum of appearance of the E_s layer occurs almost always during the day, close to noon.

The authors of the cited papers[54–57] therefore unanimously agree that the main factor causing the sporadic ionization in polar regions is the corpuscular radiation from the sun, i.e., the same agent that causes polar aurorae and magnetic disturbances. A very weighty additional argument in favor of the decisive role played by the corpuscular streams in the formation of the polar ionosphere are, in the opinion of V. M. Driatskii and A. S. Besprozvannaya,[55] certain features which they observed in the behavior of the F_2 layer, for example the large value and frequent variability of the critical frequencies f_{0F_2} in the regions near the pole during the winter season.

Certain attempts were made to find a direct correlation between the sporadic E_s ionization and the visually observed polar aurorae (and also the magnetic disturbances). Mention can be made of the papers by Knecht,[59] F. Ya. Zaborshchikov and N. I. Fedyakina,[60] and Ya. I. Fel'dshteĭn.[57] The first of these investigations, carried out in Barrow (Alaska) covered ten nights during a period of considerable auroral activity (spring equinox). The results obtained by Knecht can be summarized as follows:

a) If the polar aurora was observed close to the zenith region and was not excessively strong in visual brightness (less than four balls in the four-ball scale), a clear cut correlation could be established between the brightness of the glow and the limiting frequency of reflection from the E_s layer (Fig. 14). The frequency f_{E_s}, and consequently the electron concentration, increase with increasing activity of the polar aurora.

b) There were some exceptions to this rule, namely: no reflections from the sporadic layers were observed, firstly, in the case of very weak aurorae ($\cong \frac{1}{4}$ ball), and secondly in the cases of strong aurorae reaching four balls. The last fact can be attributed to the strong increase in absorption in the short-wave band during the time of intense flashes of "auroral" activity.

c) The minimum frequencies f_{E_s} observed during the time of polar aurorae are 5.5 – 6 Mc (the apparatus sensitivity was in the range from 1 to 15 Mc).

Analyzing these data, Knecht deems it possible to propose that the penetration of the corpuscular stream causes a specific "auroral" ionization E_a, considerably greater than the sporadic E_s ionization, which is not connected with the aurorae. Results akin to the foregoing, but analyzed in much less detail, are also given in reference 60. Finally, according to Fel'dshteĭn,[57] the auroral type of E_s ionization (E_{sa}) is always accompanied by polar aurorae, which occupy a considerable area in the zenith region.

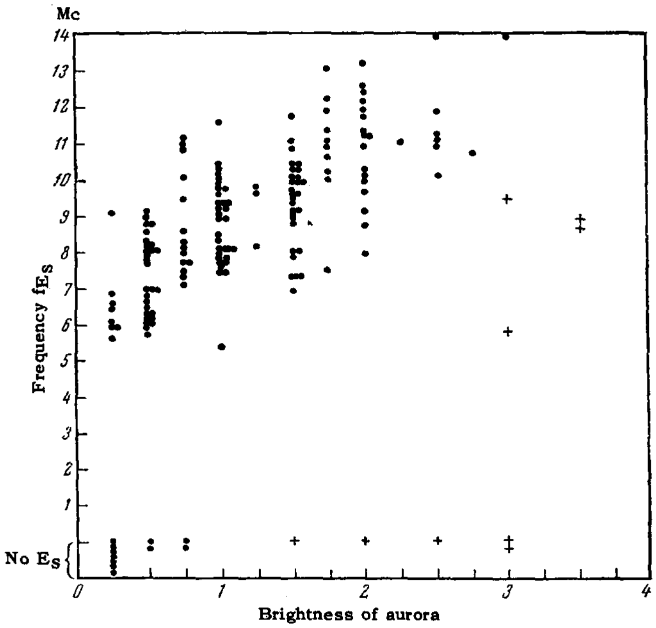


FIG. 14. Connection between the limiting frequency f_{E_s} and the aurora brightness (in the four-ball scale) (after Knecht[59]).

The substantial difference in the nature of the medium-latitude and "auroral" sporadic ionization manifests itself quite characteristically in investigations of long-distance ionospheric propagation of UHF. This question was investigated, for example, by Bailey and others.[7] In those cases when the communication channel passes through the zone of polar aurorae, amplitude bursts of the continuous signal were observed as a rule at entirely different times of the day than in the case of medium-latitude paths, as can be seen from Fig. 15, taken from reference 7.

On the medium-latitude pass from Cedar Rapids to Sterling (distance 1243 km, frequency 49.8 Mc) the intensity of the signal is increased by the appearance of the E_s ionization predominantly during the daytime, although the probability of reflections of this type is quite high even during the rest of the day (upper part of Fig. 15). For paths located near the auroral zone (see the lower histograms on Fig. 15), the anomalous intense "E_{sa} propagation" is observed only during the night hours; reflections of this type do not appear during the day at all. Such a daily variation is in full agreement with the probability of appearance of E_{sa} ionization in the zone of the polar aurorae and is quite similar to the diurnal distribution of radio reflections shown in Figs. 6 and 7. This coincidence can be understood if it is assumed that the same regulating factor is effective in both cases and that this factor in all probability is the solar corpuscular radiation.

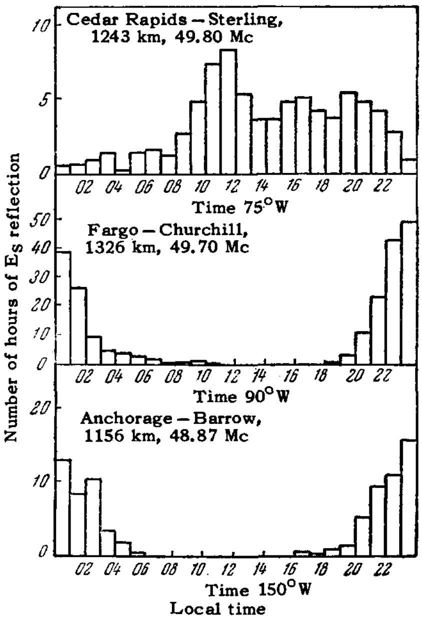


FIG. 15. Probability of passage of signals due to E_S reflections on different paths at different times of the day (after Bailey et al.[7]).

UHF propagation near the zone of polar aurorae (particularly during the time of strong disturbances) is also characterized by the fact that it is accompanied by considerable fluctuations of the average intensity of the signal and by an increased frequency of fading, which increases from several to several hundred cps.[2,7,32] (We note an interesting experiment by James et al.[61] to investigate the behavior of a signal passing through the "auroral" disturbed zone. A transmission line involving reflection from the moon was used. A 10-kw transmitter operating on 440 Mc was located in College, while the receiver was in Ottawa. It was observed that during periods of high auroral activity the level of fading increased and rapid fluctuations occurred in the direction of the plane of polarization of the reflected signal. No increase in absorption was observed.*)

An idea of the character of the physical processes in the ionosphere during the time of penetration of corpuscular streams is gained from a simultaneous recording of the change in the signal strength at two frequencies during the time of a polar blackout[7] (Fig. 16). The sharp attenuation of the signal on 28 Mc during this ionospheric disturbance was accompanied by an increase in intensity of the 49-Mc signal at the start of the blackout; the reduction in the level of cosmic radio noise (shown in the lower part of the same figure) fixes the start and end of the blackout. The attenuation of the 28-Mc signal denotes a sharp jump in the absorption, occurring apparently at the level of the D layer; were there no simultaneous increase in the scattering in the E layer (as manifest by the behavior of the signals on 49 Mc), the jump would be still greater. Such a combination of phenomena, i.e., intense absorption on short waves and simultaneous intensification of the reflection in the short-wave part of the UHF band, coinciding in time with the start of a magnetic storm and the appearance of polar aurorae, is characteristic of propagation conditions in the polar atmosphere.

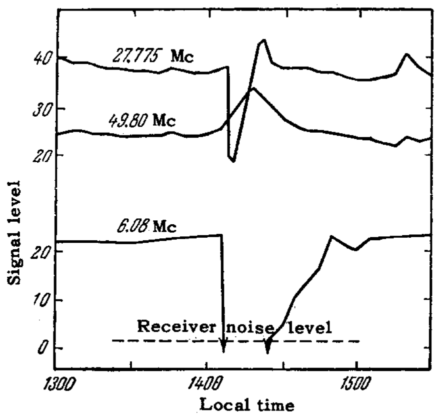


FIG. 16. Variation of the signal level on 27.775 and 49.80 Mc during the time of a polar blackout. Lower curve – level of cosmic noise at 6.08 Mc (after Bailey et al.[7]).

A special investigation of the features of "auroral" propagation of UHF waves near 40 Mc and comparison with magnetic disturbances was carried out by Forsyth and his co-workers.[63-65] The investigations covered paths located sufficiently close to the zone of the polar aurorae, or else crossing it. The distances between the transmitting and receiving points was on the order of 800 – 1200 km; it could be assumed that the radio communication between these points was by ionospheric propagation, with the reflection of the wave taking place approximately in the center of the trajectory. The work was done with cw signals. The intensity of the incoming signal was recorded automatically at the receiving points. The authors investigated and classified all the principal cases of increase in intensity of reflected signals; they were able to subdivide these into several groups and to single out the following types of reflections:

Type E. Sudden considerable increase in the level of the signal, lasting for one to three hours. The signals from meteors are lost against the background of the increased amplitude of the continuous signal from the transmitter. However, the level of the signal does not remain constant, and it is subject to slow and deep fading. No symptoms of magnetic disturbance are observed near the route for this type of ionospheric disturbance.

Type S. Relatively slow increase in the level of the signal, lasting for several hours, and accompanied by more frequent fading. Meteor signals remain visible

---

*Changes in the state of polarization after reflection from ionized regions of polar aurorae were studied by several investigators (see reference 62). As a rule, the reflected signal is almost completely depolarized. The intensity of the reflected signals depends little on the plane in which the radiation of the transmitter antenna is polarized (vertical or horizontal).

against the background of the increased amplitude of the transmitter signal. No accompanying magnetic disturbances are observed.

Types A_1, A_2, and A_3. Common to all three is the presence of simultaneous magnetic disturbances. In reflections of type A_1 there occurs a sharp and considerable increase in the signal, accompanied by rapid fading; in reflections of type A_2 a sharp increase in signal is observed, as in the case of A_1, but it is accompanied by slow and deep fading; type A_3 reflection is similar to type S, but it is accompanied by a magnetic disturbance. Examples of all three reflections are shown in Fig. 17. No simultaneous development of polar aurorae was observed in type E and S reflections, nor are there any noticeable aurorae in type A_3 reflections. Reflections of type A_1 and, particularly, of type A_2, were accompanied in a large number of cases by polar aurorae.

A continuation of the experiments with somewhat less sensitive apparatus (see the paper by Forsyth, Green, and Mah[65]) has confirmed that this classification is appropriate and not all accidental. However, as the sensitivity is reduced the type S and A_2 reflections (which will be denoted simply A) become predominant. The "auroral" type A reflections were found to gravitate definitely towards the zone of the polar aurorae and to have a maximum at about local midnight. The type S reflections had a clearly pronounced daytime maximum (12 — 14 hours local time), and were somewhat less frequent in the zone of polar aurorae than to the south or to the north of this zone. Since directional antennas were used for transmission and reception, the experiments of Forsyth et al. made it possible to ascertain, to a certain extent, the difference in the geometrical conditions of reflection in all these cases. Anticipating somewhat the discussion of the geometry of the reflections (see Sec. 4), let us report the results of these experiments. The type A_1 and A_2 reflections were found to depend on the angle between the radar beam (its wave vector) and the magnetic force line. For A_1 reflections this angle differed very little from 90°, which, in light of the Herlofson-Chapman hypothesis, denotes a reflection close to specular; for A_2 reflections, the deviations from the specular angle reached 30 — 40°.

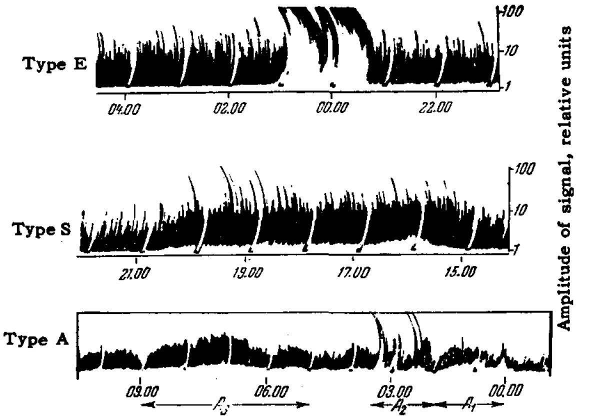


FIG. 17. Record of the behavior of a continous signal on 39.22 Mc on the path from Greenwood to Ottawa for different types of ionospheric disturbances (after Collins and Forsyth[64]). Individual frequent peaks – meteor signals.

No selectivity of reflection with respect to any angle was observed in the other types of reflection (A_3, E, S).

In the authors' opinion, type E reflections are not connected with polar aurorae or with magnetic disturbances, and result from passage of normal type E_s ionized clouds. The similarity between reflections of type S (without magnetic disturbances) and A_3 (accompanied by magnetic disturbances) implies a similarity in the structure of the ionized formations, which are apparently weakly anisotropic. The nature of the ionizing factor responsible for the appearance of the S reflections, and possibly not connected with the zone of polar aurorae, is left unexplained by the authors. The appearance of type A reflections is due, in the opinion of Collins and Forsyth,[64] to the penetration of corpuscular streams. The weak anisotropy of the ionospheric inhomogeneities in the case of A_3 reflections is attributed by these authors to the turbulent-mixing factor at relatively low levels of the ionosphere, where the ordering action of the magnetic field cannot become well pronounced. Starting out with this assumption, the A_1 and A_2 reflections, which are characterized by an appreciable anisotropy of the reflecting formations, are considered by the authors to lie higher than the A_3 type, and to be due to the action of rather intense corpuscular streams on the ionosphere.

To conclude this section let us consider briefly certain data on daytime reflections. As was already indicated (Sec. 1), the general rule in most stations is a sharp reduction in the number of reflected signals (or a complete vanishing of the signals) during the daytime, approximately between 9 and 14 hours local time. This is not a trivial fact, since it is not directly obvious why the auroral radio reflections behave in this fashion. In the earlier investigations, optimistic forecasts were frequently made that the polar aurorae, which cannot be seen during the daytime, may perhaps be detected and investigated with the aid of radar reflections. The actual diurnal variation of the reflection probability has refuted these assumptions. Taking into account all the factors in the correlation of the radio reflections with magnetic distrubances and with polar aurorae, we can apparently draw the important though tentative conclusion that as a rule there are no "daytime polar aurorae" on earth. Only a few years ago such a statement could not be corroborated by any direct proof, and the absence of polar aurorae during the day could mean simply that they could not be observed. (A certain attempt was made by Paton and Ellison[66,67] to observe aurorae near Iceland during the total solar eclipse of 1954. They noticed no signs of aurorae.) At the same time it should be noted that the interpretation difficulties involved in the theory of polar aurorae and magnetic storms, which is based essentially on the penetration of corpuscular streams into the atmosphere, have recently increased rather than decreased. Whereas the Störmer theory was able to offer a ready explanation for the arrival of the corpuscles on the dark side of the earth, the situation now becomes more complicated by the inclusion of the earth's radiation belts, which are reservoirs of corpuscles in outer space closest to the earth. The laws that govern the "shaking out" of corpuscles from the radiation belts during instants of instability are much less clear than the regularities in the penetration of corpuscles in direct streams from the sun.

It can be assumed that although the clearly pronounced daytime minimum of radio reflections from the auroral zone has not yet been explained, it emphasizes at any rate the corpuscular nature of the agent responsible for the combination of "auroral" processes.

That radio reflections are rarely observed during the daytime is only a general rule. In some stations this is not the case at all. There are stations where daytime reflections are observed quite regularly, although the intensity of the daytime activity is usually less than during the night. It is difficult to decide what role is played here by the characteristics of the apparatus, by its sensitivity, and by other parameters. We have already mentioned the S reflections of Forsyth et al.[64,65] Analogous observations in slant sounding (Kemi-Kiruna, path 310 km, frequency 92.8 Mc) are described by Egeland, Hultquist, and Ortner.[68] They fixed the daytime maximum at 12 — 16 hours local time, and the daytime and nighttime signals are of analogous character.

Ya. G. Birfel'd[44] gave a thorough summary of the features of reception of daylight reflections in many stations of the Soviet Union, and indicated also the bursts of reflections which he observed during daytime and morning hours during periods of chromospheric flares.[8] Interesting data are reported by Presnell et al.[34] on radio sounding of aurorae in College (Alaska) at microwave frequencies (216, 398, and 780 Mc). Reflections at the first two frequencies occurred regularly in parallel with reflections at 41 Mc, and both types of signals (diffuse and discrete) occurred under well defined conditions. The discrete signals were observed only when the reflecting region was not illuminated by the sun. Diffuse signals, to the contrary, occur preferably during daytime hours. Unlike the observations of Forsyth,[64,65] both types of reflections corresponded to an increase in magnetic activity. Work with very high frequencies has made it possible for the authors to show that the regions reflecting these two types of signals are of quite different structure: the discrete nighttime signals correspond to a vertical reflecting surface (with generatrices apparently parallel to the force lines of the earth's magnetic field), whereas the diffuse signals are reflected from a horizontal layer. The height of the reflections corresponds in either case to the level of the E layer in the ionosphere.

Other observations of daytime UHF radio reflections are also reported in the literature;[5,69] some have been reported by observers located far away from the auroral zone, in medium or even tropical latitudes. The sum total of this material is not sufficient to permit any conclusions concerning the nature of the "daytime" UHF reflections.

4. GEOMETRY OF RADIO REFLECTIONS

As was indicated in Sec. 1, the main features of the "geometry" of radio reflections from polar aurorae are as follows: there are reflections at considerable angles to the horizon, the ranges are predominantly greater than 400 — 500 km (with tendency for the range to increase at high-latitude stations), and the reflecting regions are essentially located in the northern quadrant relative to the station, independently of the geophysical latitude of the station (in the northern hemisphere).

Since it was already stated that the "auroral" reflections come approximately from the level of the E layer, the first two of the foregoing features are obviously interrelated. The upper limit of the range (approximately 1200 — 1400 km) for direct reflections can be determined by the fact that the farther regions are hidden behind the observer's horizon.

Several hypotheses have been proposed to explain the "aspect" features of ionospheric reflections, connected with magnetic disturbances and polar aurorae. The principal, now generally accepted, interpretation is the Herlofson-Chapman hypothesis, while the others are now of historical interest only.

Thus, Forsyth, Currie, and Vawter[19] advanced the hypothesis that the angle effect is due to strong absorption in the layer located directly below the reflection zones. However, the necessary absorption is apparently not attained in fact. According to McKinley and Millman[25] the attenuation of cosmic noise, observed during the time of polar aurorae, reaches in the corresponding frequency range only several decibels, whereas the attenuation called for in the hypothesis of Forsyth et al. should reach several times ten of decibels.

According to calculations by Chapman and Little,[70] the increase in absorption at 30 Mc during the time of polar aurorae, at heights of 80 — 90 km, amounts to approximately 2.5 db.

Harang and Landmark,[22] making use of certain peculiarities of the reflections which they observed at two different frequencies, have proposed that the radio echo obtained during the time of polar aurorae is the result of double reflections from the earth's surface and from the ionosphere. The angle effect, in the opinion of Harang and Landmark, is determined not by the anisotropy of the reflecting formations, but by the existence of different limiting angles of incidence when operating at different frequencies. In radio transmission practice this effect is well known and is taken into account by the "minimum-usable-frequency factor." The frequency peculiarities of the reflections observed by Harang and Landmark were not confirmed in subsequent experiments.

The explanation of the "aspect sensitivity," now accepted by most researchers, was first proposed by Herlofson.[15] In the development of this idea, Chapman[38] published a paper containing formulas, tables, and graphs for the calculation of the "geometry of radio reflections." According to the Herlofson-Chapman hypothesis, the "aspect sensitivity" of radio reflections from polar aurorae, just as the features of the reflections from meteor trails, is due to the anisotropy of the reflecting ionized formations. In the case of polar aurorae, the factor that governs the character of the anisotropy is the earth's magnetic field. It is proposed that the reflecting centers of the "auroral" ionization lie along the force lines of the field, forming structures that are stretched out along these force lines. If we admit that the reflection on the boundary surfaces is close to specular, the aspect sensitivity is easy to explain. As in the case of meteor trails, the optimum conditions for reflection will occur when the radio beam is perpendicular to the reflecting surface.

Chapman[38] calculated the geometric loci of the points of reflection, giving the configuration and position of the "auroral reflecting surfaces" for different observer positions. Chapman considered only the field of a centered dipole and made no attempts to take a more rigorous account of the earth's real field; nor did he consider refraction of radio waves in the troposphere and in the lower layers of the ionosphere. Chapman's principal results are illustrated in Figs. 18 – 20.

For a station Q (Fig. 18) with a geomagnetic latitude φ, the geometric locus of the points of reflection is determined by the requirement $(\mathbf{H}\cdot\mathbf{r})_{QP} = 0$, that the magnetic field intensity vector $\mathbf{H}$ at the point P be perpendicular to the radius vector $\mathbf{r}$ drawn from Q to the same point.

Chapman's "auroral" reflecting surface is represented in Cartesian coordinates by a third-degree algebraic equation. Figure 18 shows the intersection of this surface with the meridional plane (passing through Q and through the dipole) for a point Q with geomagnetic latitude $\varphi = 45°$. The dotted part of the curve is located under the earth's surface and is obviously of no interest in the problem of radio reflections. Parts of the curve located below the line $P_N - P_S$, i.e., below the observer's horizon (also in first approximation), are inactive from the point of view of production of reflections. Only the portions located above the observer's horizon contain points from which reflections can be received. For this it is necessary, however, that the ionization in the corresponding regions of space be sufficient. This means that in practice one can consider apparently only those parts of the Chapman surface which are located not lower than 80 – 90 km above the earth's surface. Figures 19a and 19b show parts of the meridional curve located at high latitudes relative to the observer, for observation stations with $\varphi = 64°$ and $\varphi = 56°$. Chapman discusses the possibility of the arrival of reflections from equatorial zones, too (section P_S of the curve of Fig. 18), but no actual reflections of this kind have been observed.

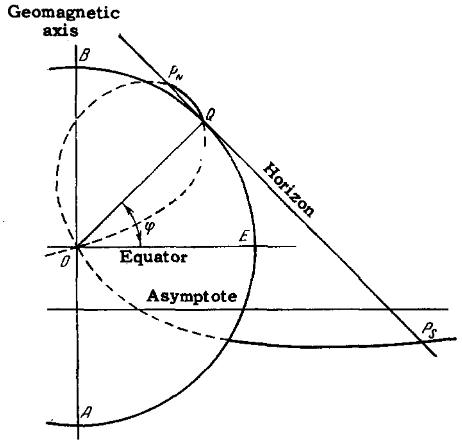


FIG. 18. Meridional section through the Chapman surface corresponding to the perpendicularity requirement $(\mathbf{H}\cdot\mathbf{r}) = 0$ (after Chapman[38]).

The intersection of the Chapman surface with a horizontal plane containing the point of observation yields a curve which is nearly a circle when φ is not too small (see curves marked $\theta = 0$ on Fig. 20, for $\varphi = 60°$ and $\varphi = 45°$).

For sections with planes with specified elevation angles (in the meridional plane), the reflection points lie on oval lines. Finally, the intersections between the Chapman surfaces and spheres of radii $R_0 + h$ (where R_0 is the earth's radius), concentric with the

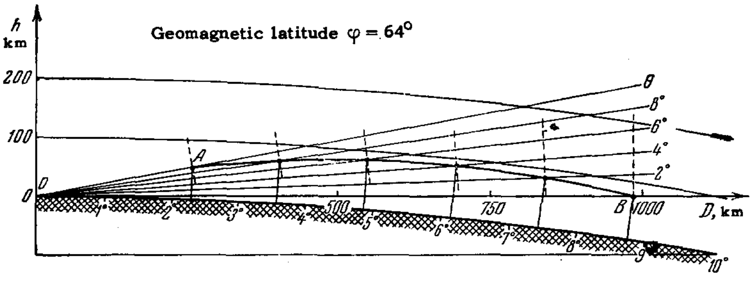


FIG. 19a. Chapman's reflecting surface (meridional section) for a station with geomagnetic latitude $\varphi = 64°$. OD – observer's horizon with range scale (kilometers); θ = elevation angle. The dotted lines are drawn in the direction of the geomagnetic field lines.

FIG. 19b. Chapman's reflecting surface (meridional section) for geomagnetic latitude $\varphi = 56°$ (see also caption to Fig. 19a).

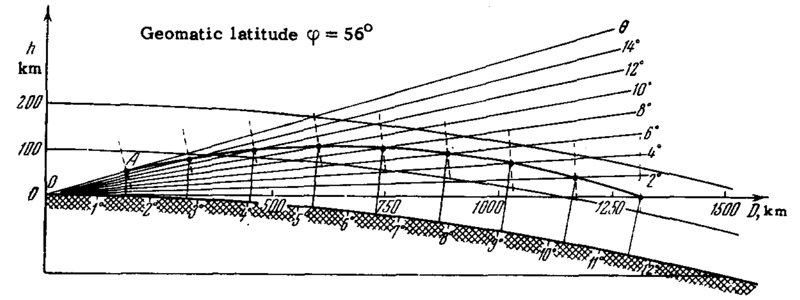
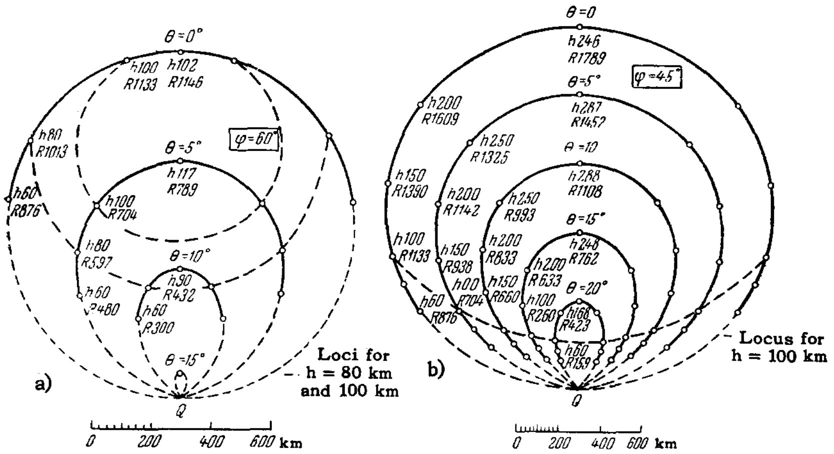


FIG. 20. Intersection between Chapman's surface and planes with given elevation angles θ in the meridional plane (solid curve) and spheres concentric with the earth's surface at specified distances h from the earth's surface (dashed lines). a) $\varphi = 60°$, b) $\varphi = 45°$. The numbers following the letters h and R denote the height and range of the corresponding point in kilometers (after Chapman[38]).



earth's surface, yield the so-called "Chapman loci," i.e., the positions of the points of optimum reflection, corresponding to a specified reflection height h (Fig. 20a shows dotted the loci for h = 80 and h = 100 km; Fig. 20b shows the locus for h = 100 km). If the reflecting ionized auroral regions are actually localized in a certain narrow interval of heights, the "locus" gives the space position of the zone responsible for the reflections.

The question of the cause of the anisotropy of the ionization is not considered by Chapman. However, both Herlofson and Chapman, as well as some other authors, regard it as self-evident that the ionization along the lines of the earth's magnetic field can be produced directly as a result of the corpuscules that penetrate into the atmosphere. Booker, whose ideas will be discussed in Sec. 5, holds to a different opinion in this matter.

"Chapman's scheme" was a splendid working tool and very successful in interpreting results of radio observations of polar aurorae. One may think therefore that its underlying ideas are correct. Yet it is evident that it is based on an essential idealization. This is seen from the fact that in many cases the observed "reflection geometry" does not fit the Chapman scheme. It agrees much better with medium-latitude observations than with high-latitude ones. Thus, the greater part of the reflections obtained in Murmansk, College (Alaska) or Tromso (Norway) should be interpreted by the Chapman scheme as reflections from surfaces located lower than 80 — 85 km (see Fig. 19a), i.e., at the level of the minimum heights of the polar aurorae, and is appreciably lower than the actually observed reflection heights.

If the earth's magnetic field at the 100 — 150 km level is not regarded as the field of a centered dipole, then the Chapman perpendicularity requirement is much better satisfied for many stations. Such a replacement of the idealized "geomagnetic field" by a pattern of force lines connected with the local structure of the field at the earth's surface has been made by Pogorelov,[30] Unwin,[26,27] and a few others (Figs. 21 and 22).

Another point that needs refinement in the Herlofson-Chapman theory is an account of the real scattering indicatrices of the ionized "auroral" formations. If we disregard the special types of reflections at large

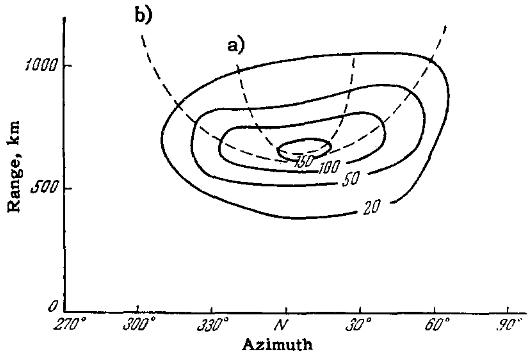


FIG. 21. Position of points of equal probability of reflection, in azimuth – range coordinates, with superimposed Chapman locus (a) and a locus drawn on the basis of the pattern of the real magnetic field (b). N – geographic north (after V. I. Pogorelov;[30] station Roshchino near Leningrad).

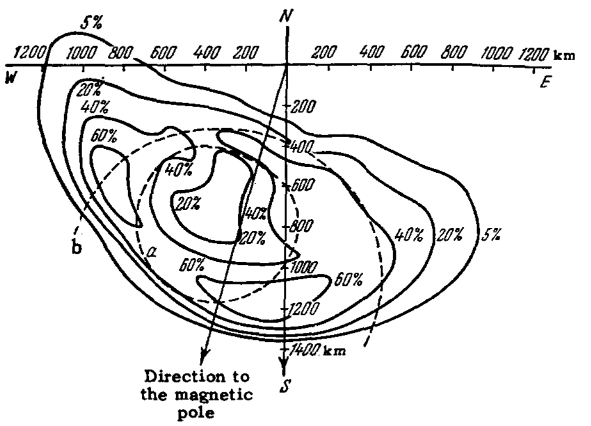


FIG. 22. Curves analogous to Fig. 21 for the Invercargill station (New Zealand) (after Unwin[27]). a – Chapman locus, b – locus based on the local magnetic field.

angles (30° — 40°) singled out by Collins and Forsyth,[64] then, according to the observations of most authors (see, for example, references 19, 26, 27, 31, 34, 71), the deviation of the reflected ray from perpendicularity usually does not exceed 5 — 15°. Assuming, for greater simplicity of calculation, that the reflecting formation is an ellipsoid of revolution (spheroid) with dimensions that are large compared with the wavelength, Kaiser obtained an approximate idea of the ratio of the semi-axes of the ellipsoid (assuming the axis of the latter to coincide with the direction of the force line). Figure 23 shows the dependence of the effective scattering cross section of the spheroid on the ratio of the semi-axes and on the angle of incidence of the wave. A semi-axis ratio of 1 : 10 corresponds to a sharp reduction in the reflecting ability at angles of incidence greater than 5° to the spheroid axis, and a ratio of 1 : 5 can explain the cases in which the reflection intensity is attenuated more slowly within approximately 15°.

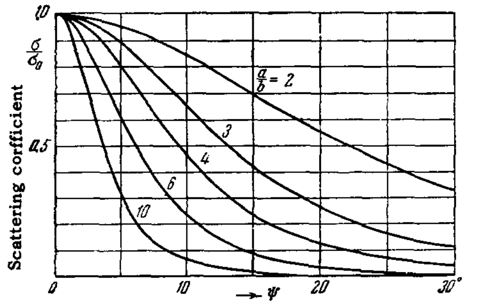


FIG. 23. Relative effective cross section as a function of the ratio of the semi-axes of the spheroid and of the angle of reflection ψ. a/b – ratio of vertical to horizontal dimension of the spheroid (after Kaiser[41]).

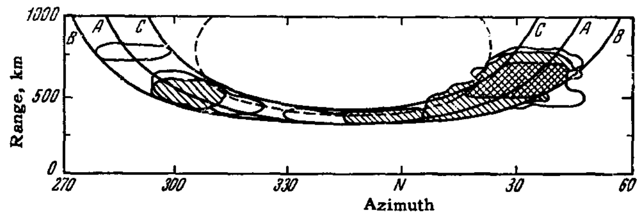


FIG. 24. Locations of the reflecting formations in space (range vs. azimuth) for the Jodrell Bank Station (after Kaiser[72]). Dashed curve – "Chapman locus"; A – geomagnetic parallel; B, C – boundaries determined by the opening angle of the beam of the radar antenna.

As was already indicated (Sec. 1), Kaiser and a group investigating radio reflections at the Jodrell Bank Station[21,41,46] adhere to their own point of view concerning the locations of the "auroral" reflecting formations. They assume that neither the "Chapman locus" nor a "locus" based on the local magnetic field fit the locations of the reflecting formations in space. In the opinion of Kaiser et al. the observed pattern of azimuth variation of the range of the echo can be explained more correctly by locating the reflecting centers along a certain fixed geomagnetic parallel. To confirm this, range vs. azimuth diagrams have been plotted. The diagram of Fig. 24, taken from the paper by Kaiser,[72] is indeed in poor agreement with the "Chapman locus" and fits better the assumed latitudinal dimension of the reflection zone. However, this effect can hardly be discerned on the diagram for the Stanford (U.S.A.) station, published in the same article. Recently Forsyth[33] returned to the question of the spatial disposition of the reflecting regions and the reasons for the "aspect sensitivity." As was already indicated, Forsyth and his co-workers did not succeed in proving the existence of strong absorption in the region below the reflection zone, and in the interpretation of results obtained with continuous radiation and bistatic (two-position) apparatus,[63,64] these authors accepted the hypothesis of reflection from spheroids oriented along the magnetic field for those cases, in which the aspect sensitivity was observed in the experiments.

In his 1960 paper, Forsyth proposes a different explanation. In his opinion, the clear-cut connection existing between a certain part of the aurorae and the radio reflections gives grounds for assuming that the reflection regions actually coincide with the regions of optical glow, although this may not always be evident to the observer. The predominant forms of the aurorae, arcs and bands, usually stretch out over many hundreds of kilometers in latitude, but have at the same time little depth (on the order of 1 km). Complex auroral shapes in the form of loops, scrolls, etc. are less frequent. The statistical probability of receiving reflections, other conditions being equal, is proportional to the intensity of the reflected signals. If it is assumed that incoherent scattering takes place, the intensity of the reflected signal will depend (for a fixed duration of the sounding pulse and a given angular beam width and distance to the target) on the diameter of the "target" and on its depth, i.e., on the size of the scattering volume.[8,33,73] Simple "flat" auroral formations are in a position favorable to the production of reflections if the beam is directed approximately along the normal to the formation, i.e., approximately to the "north" or "south" azimuth; to the contrary, the "east" and "west" azimuths are characterized by low probability of reflections from homogeneous arcs, regardless of the position of the station. In contradistinction, complex "not flat" forms of aurorae, which are more rarely encountered, will provide reflections at all azimuths with equal probability. Taking these considerations into account and bearing in mind the latitude factor in the appearance of the aurorae, Forsyth attempts to calculate the statistics of the appearance of radio reflections for the stations in Saskatoon and in College, without using any assumptions, concerning the microstructure of the reflecting ionized formations.

Forsyth's arguments can hardly be objected to, but they still do not explain fully why, according to the observed data, a sharp preference for reflections from the north is observed at College (geomagnetic latitude 64°), which is located very close to the maximum of the auroral zone, and why there is no corresponding maximum of reflections from the south. It remains unclear from this paper which factor in Forsyth's calculations for College should emphasize this predominance of the northern magnetic azimuth. Consequently the arguments advanced do not describe completely the specific anisotropic structure of auroral reflecting formations.

5. ELECTRON CONCENTRATION

Apart from Chapman's reflection scheme, which established a connection between the "aspect sensitivity" and the structure of the magnetic field, very little was done so far on a physical interpretation of the observed reflection picture.

The parameter of greatest interest for the determination of the nature of the processes, in conjunction with data on the correlation with other geophysical phenomena, is the electron concentration. Now that we have described in the preceding sections the main characteristics of the phenomena, it is natural to turn to the problem (posed at the beginning of the article) of the real values of the electron concentration in the ionized formations responsible for the UHF reflection from the auroral zones.

The complicated character of the predominant part of the reflected signals (diffuse reflections), the increased fading frequency in long-range ionospheric propagation of UHF through the zone of the polar aurorae, and the strong depolarization of the reflected waves, noted in the auroral echoes, all are evidence of a rather complicated and variable structure of the ionosphere in the region of auroral disturbances. The incoherent character of the reflection manifests itself clearly in many characteristics of the radio echoes from polar aurorae. Scattering by the fluctuating ionospheric inhomogeneities must therefore be considered to be the most important element in the mechanism of the examined radio reflections. At the same time, this mechanism is apparently not confined to scattering by random inhomogeneities, at least not in every case. This is demonstrated by the existence of weakly distorted signals in the form of discrete echoes, the duration of which is sometimes sufficiently long. That the structure of the auroral ionized formations is an ordered one is clearly demonstrated by the aspect sensitivity of the reflections. Finally, individual observations (for example, the aforementioned observations of Unwin and Gadsden[37] with a multiple-lobe antenna) provide direct evidence that extensive sharply outlined layers exist in the reflecting region during definite instants of time. It is most probable that all types of reflections listed in Sec. 1 participate in the formation of the reflections and are superimposed in various combinations, and that different mechanisms predominate in different cases. The conjunction of coherent and incoherent reflections makes the problem of calculating the values of the electron concentration rather complicated at times.

Let us illustrate by means of some calculations the results obtained when attempts are made to use the concepts of regular reflection and of coherent scattering.

As was already indicated in Sec. 1, Lovell, Clegg, and Ellyett[14] who were the first to observe the "auroral" radio reflections on a radar screen, have assumed that total reflection from an ionized cloud is involved.

Herlofson,[15] estimating the intensity of the observed reflected signals, has shown that regular reflection can be assumed only when the coefficient of reflection is very small, on the order of $\rho = 5 \times 10^{-7}$, which means, if the absorption is negligible, that the reflecting formation is almost transparent to radio waves on 46 Mc.* The electron concentration can be readily calculated by assuming a sharp boundary for the reflecting region (Fresnel reflection) and that the index of refraction differs little from unity. The Fresnel formula in the "ionospheric" notation has the form (R is the amplitude reflection coefficient)

$$|R| = \varrho^{1/2} = \frac{e^2 N}{4\pi m f^2} \tag{3}$$

(N is the electron concentration, f the frequency, e and m the charge and mass of the electron). With this

---

*The signal power delivered to the input of the radar receiver by reflections from a plane surface can be calculated by the formula

$$P_r = P_t \frac{G_t A \varrho}{16\pi D^2}, \tag{2}$$

where P_r is the received power, P_t is the radiated power, G_t is the gain of the transmitting antenna, $A = G_r\lambda^2/4\pi$ is the effective area of the receiving antenna, D is the distance to the object, and ρ is the reflection coefficient. With $P_t \cong 50$ kw, $P_r \cong 1\times10^{-13}$ w, $D \cong 500$ km, and $\lambda = 6$ m, the figure obtained for ρ is approximately 5×10^{-7}.

value of ρ we obtain for the electron concentration

$$N \cong 7\cdot 10^4 \text{ cm}^{-3}.$$

This is two or three times less than the daytime concentration in the E layer, meaning apparently that the assumed reflection from a sharp interface is wholly untenable. The low value of the reflection coefficient, according to Herlofson, may also be the result of the diffuseness of the boundary. It is easy to show that if the boundary becomes diffuse the coefficient of reflection decreases in proportion to the factor

$$C=\left|\frac{1}{N_0}\int \frac{dN}{dx} e^{i\frac{4\pi x}{\lambda}} dx\right|, \tag{4}$$

where dN/dx is the gradient of the concentration in the transition region and N_0 is the electron concentration far from the boundary. If the transition layer is approximated by means of the formula

$$\frac{dN}{dx}=\frac{N_0}{a\sqrt{\pi}} e^{-\frac{x^2}{a^2}}, \tag{5}$$

we obtain after integration

$$C=e^{-\frac{8\pi^2 a^2}{\lambda^2}}, \tag{6}$$

from which it follows that the thickness of the transition layer should be on the order of several meters ($a \cong 3$ m if $C \cong 10^{-6}$.

Herlofson admits the possibility of such a structure for the surface of the reflecting layer, although he believes that an inhomogeneity with so large a gradient would dissolve in the ionosphere quite rapidly (< 20 minutes).

We see that these estimates are rather approximate in character. However, apparently the fluctuations of the gradients of the electron density in the reflection zone can actually lead to instability of the amplitudes of the reflected signals and to a variable form of the envelope on the amplitude-time display, as is particularly emphasized in several papers by Ya. G. Birfel'd.[8,44]

Aspinol and Hawkins[16] also interpreted the results of their observations by using the Fresnel reflection hypothesis. A formula analogous to (3) for reflections from a double-curvature surface has the following form

$$P_r^{1/2}=\frac{k\varrho^{1/2}\lambda}{D_0}\left[\frac{ab}{(a+D_0)(b+D_0)}\right]^{1/2}. \tag{7}$$

Here a and b are the radii of curvature of the surface ($a, b \gg \lambda$) and k, in accordance with (2), is equal to

$$k=\frac{P_t^{1/2}G}{8\pi}, \tag{8}$$

where P_t is the radiated power and G the gain of the radar antenna.

In the case of a plane interface, Aspinol and Hawkins obtained, like Herlofson, an electron concentration on the order of $N \cong 10^4$ cm^{-3}. However, the Fresnel reflection from a cylinder with curvature radii $a = \infty$ and $b = 1$ km leads already to a concentration $N = 6 \times 10^5$ cm^{-3}. The existence of such cylinders or columns of ionization is feasible from the point of view of optical observations: the long vertical rays of polar aurorae have a diameter on the order of 1 km. Aspinol and Hawkins did not consider reflection from a combination of many similar formations (rays in a curtain or a band of rays), although such a case should be the more typical if we consider the most probable conditions of correlation between radio reflections and the visual picture of the aurorae. But the calculation of reflection from an irregular structure of this type would obviously be too arbitrary, even if it were to be of any use at all.

Hellgren and Meos,[18] in an analogous calculation of the reflection from a cylindrical surface on 30 Mc, obtained a value 2×10^6 cm^{-3} for the electron density. They measured in addition the average time of signal fluctuation. If the effective coefficient of recombination in the E layer has during the time of the aurora its usual value, approximately 1×10^{-8} cm^3/sec, then the relaxation time ($t = 1/\alpha N$, where α is the recombination coefficient and N the electron density) is found to be approximately 45 sec. This, according to Hellgren and Meos, is also the average period of the fluctuations of the reflected signal, confirming, in their opinion, the correctness of their estimate of N.

The average coefficient of reflection from a certain regular reflecting surface and the corresponding average value of the electron concentration were calculated by Seed[71] (New Zealand Radio Observatory). By relative calibration of the intensities of the signals corresponding to different ranges, the author attempted to ascertain the general character of the form of the reflecting surface. An attenuation obeying approximately a D^{-2} law has enabled the author to assume that the reflections come from a certain plane or from an aggregate of discrete radiators distributed over a plane. The formulas, which have already been given above, yield in this case a value for the coefficient of reflection on the order of

$$\varrho \cong 2\cdot 10^{-7},$$

and the average electron concentration is found to be in the range

$$2.4\cdot 10^4 < N < 7.5\cdot 10^4 \text{ cm}^{-3} \tag{9}$$

The author does not assume that such a concentration is uniformly distributed over a large volume, and considers the scattering surface to consist of discrete coherently-scattering radiators. The observed azimuthal distribution of the signal fits an aggregate of cylindrical radiators best of all. The author draws no conclusion whatever concerning the dimensions and spatial distribution of these radiators, nor does he determine the true electron concentration in these radiators (the critical concentration is no exception).

The conditions for incoherent reflection (scattering) and the determination of the parameters of the scattering inhomogeneities have been the subject of many investigations, mostly recent. The possibility of estimating the values of the electron concentration on the basis of direct radio-reflection data are quite unclear in this case. Kaiser[41] favored the hypothesis of total (critical) reflection from the inhomogeneities connected with the polar aurorae, leaning, for example, on the following arguments. Firstly, in the partial reflection hypothesis the values of the concentrations, which are close to critical (see references 16 and 18), should fluctuate strongly, in view of the variability of the polar aurorae. It would be logical to expect in individual instants of time sharp peaks of reflection intensities, something which does not occur. Secondly, allowance for a finite concentration gradient at the interface leads (for λ on the order of several meters) to a boundary layer whose effective thickness is hardly more than several decimeters. To assume a stable existence of such transition layers at an altitude of 100 — 120 km in the atmosphere is impossible, for this is also the average mean free path of the molecules at that level.

The difficulties of obtaining a correct picture of the "auroral" ionization are apparently closely related with the fact that the characteristic spatial parameters of the auroral ionospheric inhomogeneities are close to the wavelengths used for sounding. A method by which these difficulties can be overcome in some manner and the indeterminacy in the estimate of the character of the reflection eliminated, is the parallel use of several frequencies. Forsyth and Vogan,[63] and later Collins and Forsyth, made an attempt to use this method for an experimental estimate of the electron concentrations in the reflecting volumes.

Forsyth and his co-workers used three radars in simultaneous operation on 32.22, 39.22, and 48.82 Mc, and identical antenna installations. Two-position operation was used: the receiver and transmitter were separated by approximately 1000 km. The reflection region was assumed to be located near the middle of the ray trajectory, at the height of the E layer. Unmodulated transmission was used.

If we denote by A the amplitude of the signal at the receiver input, then the power gathered by the receiver antenna can be expressed as

$$A^2 P'_r = \frac{P_t G_t C_r \lambda^2}{64\pi^3 D_1^2 D_2^2} S, \tag{10}$$

where P'_r is the input when A = 1, S is the effective radar cross section of the target,* and D_1 and D_2 are the distances from the transmitter and from the receiver to the target.

Upon substitution of the apparatus parameters* we obtain the following working formula for S:

$$S = 2{,}5 \cdot 10^6 \frac{A^2}{\lambda^2} \ (м^2). \tag{11}$$

The amplitudes observed by the authors corresponded to the values of the effective cross sections from 2×10^4 to 4×10^7 m^2. In reflection from a surface this would mean a reflection coefficient from 2×10^{-8} to 10^{-5}. If the dimensions of the reflector are much smaller than the Fresnel zone and can be characterized by a certain definite cross section (S = const), the amplitude of the signal A will be proportional to λ. Noting that "such a relation obtains frequently, even when the reflection process cannot be ascribed to a definite physical cross section," the authors investigate the character of the actual wavelength dependence of the "reduced amplitude" A′ = A/λ, observed in their measurements. The theoretical dependence of A′ on λ for certain types of ionospheric reflection and scattering, is known from estimates contained in several papers:

1. Partial (Fresnel) reflection from a plane layer, in which the electron concentration is much less than critical; the interface is sharp (Herlofson[15]). According to Eq. (3), the coefficient of reflection is $\rho \sim \lambda^4$, i.e., $A^2 \sim \rho\lambda^2 \sim \lambda^6$ and, consequently,

$$A' = \frac{A}{\lambda} \sim \lambda^2. \tag{12}$$

2. Scattering by isotropic inhomogeneities with low electron density (Bailey et al.[7]). The scattering coefficient σ is proportional to $(1 + k/\lambda^2)^{-1}$, where k is a factor that depends, other conditions being equal, on the scattering angle. Since $A^2 \sim \lambda^2\sigma$, we have for small scattering angles

$$A' \sim \sigma \sim \left(1 + \frac{k}{\lambda^2}\right)^{-1}; \tag{13}$$

in the case of large-angle scattering or when the inhomogeneities are much larger than the wavelength, k ≫ λ and (13) goes into (12).

3. Scattering by non-isotropic elongated inhomogeneities with low electron density (Booker[74]). In backward scattering (reflections of the radar type) the scattering coefficient σ is found to be proportional to $\exp(-k_1/\lambda^2)$, and consequently

$$A' \sim e^{-\frac{k_1}{\lambda^2}}, \tag{14}$$

where k_1 is a certain factor.

4. For very thin and long weakly ionized columns this dependence goes into (see reference 16)

$$A' \sim \lambda^{\frac{1}{2}}. \tag{15}$$

When the ionization is greater than critical, an entirely

---

*The radar effective cross section is defined as:[76]

$$S = \lim 4\pi D^2 \left| \frac{W_r}{W_i} \right|,$$

where W_r is the flux density of the energy scattered in the direction towards the receiver at a distance D from the scatterer, and W_i is the flux density of the energy incident on the scatterer.

*$G_t = G_r = 10$, $D_1 = D_2 = 500$ km, $P_t = 0.1$ kw; the unit input amplitude is taken to be 10^{-7} v.

different situation should prevail. If the dimensions of the highly ionized inhomogeneities are sufficiently large, the reduced amplitude will not depend on the wavelength and will be determined only by the ratio of the dimensions of the inhomogeneity to the size of the first Fresnel zone. As noted by Forsyth, Vogan, and Collins,[63,64] and as emphasized earlier by Kaiser,[41] the difference between the two types of reflections denotes instability of the reflections if the length of the reflected wavelength is close to critical.

Starting out with these considerations, Forsyth and his co-workers measured the ratio of the reduced amplitudes of the reflected signals, using three radars simultaneously. Denoting the reduced amplitudes by A_6', A_8', and A_9', in accordance with the wavelengths of the radars, and denoting their ratios by

$$X=\frac{A_8'}{A_6'},\quad Y=\frac{A_9'}{A_8'},\tag{16}$$

the authors plotted the measurement in X and Y coordinates (Fig. 25). The part of the diagram for which $X > 1$ and $Y > 1$ is divided into three regions in accordance with the following conditions:

region I: $Y>2,\quad X<Y$;

region II: $X>2,\quad Y<X$;

region III: $X<2,\quad Y<2$.

If all the reflections occur at less than critical density (partial reflection), the observed values of X and Y should be located predominantly in region III. On the other hand, if the mechanism of total reflection is also in action, then the experimental points can apparently extend over the entire X–Y diagram. In this case the following three variants are possible:

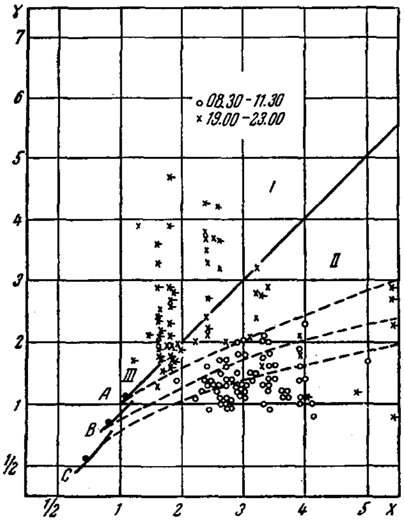


FIG. 25. X–Y diagram of the observed data (after Collins and Forsyth[64]). Point A, the adjacent segment of the solid line, and the dashed curve correspond to Eqs. (15), (13), and (14), respectively. The shifts of curves B and C are to allow for absorption (10 and 20 db for λ = 9 m).

1) The average electron density $\overline{N}$, in the ionized reflecting volumes, is greater than the critical density N_9 for $\lambda = 9$ m, but is less than N_8 for $\lambda = 8$ m; then

$$A_9' > A_8' \cong A_6'$$

and consequently, $Y \gg X \cong 1$; the experimental points lie in region I.

2) Analogously, if $N_6 > \overline{N} > N_8$, then $A_9' \cong A_8' > A_6'$, and consequently $X \gg Y \cong 1$. The points will lie in region II.

3) $\overline{N} \geq N_6$, i.e., the electron concentration exceeds critical for all three wavelengths. In this case $A_9' \cong A_8' \cong A_6'$ and consequently $X \cong Y \cong 1$; we can expect all the experimental points to lie in region III.

The circles and crosses in Fig. 25 correspond to two different observation periods (08:30 — 11:30 and 19:00 — 23:00, Greenwich time March 3, 1956). The points of the first period are concentrated predominantly in region II (Y close to 1, X scattered), while the points of the second period lie in region I (X close to 1, Y scattered). In accordance with the author's interpretation, we should conclude that the electron density during the first period, i.e., in the hours past midnight (local time), was greater than $N_8 = 1.9 \times 10^7$ cm^{-3}, but did not exceed $N_6 = 3.0 \times 10^7$ cm^{-3}; in the afternoon hours local time (second period) the electron density was apparently less than N_8, but exceeded $N_9 = 1.3 \times 10^7$ cm^{-3}.

The work of Collins and Forsyth[64] is interesting because it contains the first attempt at experimentally estimating the electron densities in ionized formations of the polar aurorae. At the same time, this investigation is a clear example of how complicated the problem is.

It should be mentioned in connection with the work of Forsyth et al.[63,64] that the statistical properties of auroral ionized reflecting formations are discussed in a recent paper by McNamara.[75] Without aiming at an investigation of the reflection mechanism, but being interested essentially in the effective size of the inhomogeneities, McNamara found that the statistical distribution of the intensities of the "auroral" signals agrees well with a power-law or exponential distribution of the probability p (X) of the effective radar cross sections, namely

$$p(S)=\frac{k}{S^m},$$

or

$$p(S)=\frac{1}{S_{\max}}e^{-\frac{S}{S_{\max}}}.$$

Naturally, the model of an ionosphere consisting of a large number of individual fluctuating inhomogeneities is not new. An analysis of the properties of a "turbid," incoherently scattering ionosphere is for example, the subject of papers by Ya. L. Al'pert,[76-78]

A. A. Aĭnberg,[79] and others. In some of these investigations (see, for example, reference 77), numerical values have been obtained for many statistical parameters of the unperturbed ionosphere, such as the random velocity of motion of the inhomogeneities, the angular and linear dimensions of the inhomogeneities, the fluctuations of the electron density, and others. These calculations have not yet been applied to the perturbed state of the polar ionosphere and to an explanation of the "auroral" radio reflections. Many interesting points of view concerning the physical nature of ionospheric irregularities in the E layer and the parameters that they must have to scatter UHF waves effectively are contained in the papers of Ya. L. Al'pert[77] and Booker.[74] Since Booker is especially after an interpretation of auroral radio reflections with account of the anisotropy of the inhomogeneities, we shall discuss this paper in greater detail.

UHF reflections from polar aurorae are of special interest in the general study of ionospheric inhomogeneities. On the one hand, "auroral" inhomogeneities have many peculiarities not possessed by the ionosphere at other latitudes; these are obviously connected with geomagnetic disturbances and the corpuscular penetrations. Their nature is in all probability inseparable from the nature of the latter. At the same time, the observed analogies with certain effects that occur at medium and low latitude suggest that at definite times the penetration of corpuscular streams into the upper atmosphere plays an essential role in the state of the ionosphere. It is quite obvious by now that along with an account of the action of strong non-permanent corpuscular streams, which produce intense geomagnetic disturbances and other clearly pronounced geophysical effects, one must not neglect the existence of a corpuscular "background" continuously bombarding the earth.[40,55] This background may, for example, cause the ionization in the E and F layers during the polar night, the glow of the night sky, etc. The mechanism of interaction between the corpuscular streams and the magnetic field of the earth and the processes that accompany the penetration of the corpuscles into the atmosphere are far from clear. The earlier theories took account primarily of the possibility of corpuscles arriving directly from the sun and entering into the upper atmosphere of the earth. As our knowledge of the outer space surrounding us increases, the question can evidently be treated differently. The earth has a constant reservoir of corpuscles in the form of "radiation belts," which are the source of corpuscular bombardment of the upper atmosphere during the time of the disturbances. It is not excluded that many corrections and modifications will have to be introduced into the basic premises of the theory of polar aurorae and magnetic storms; it is universally known that there were many contradictions in the old theories. Thus, for example, serious difficulties arose in estimates of the absolute values and velocity distributions of the "auroral" protons from observations of the spectra of the polar aurorae, of the depth of penetration of the corpuscles and their composition, etc. The particle energy in corpuscular streams is still uncertain; according to various assumptions, it may range from 10^3 to 10^6 ev. The point of view that the auroral ionospheric inhomogeneities are essentially produced by an aggregate of ionized tracks of penetrating corpuscles (Sec. 4) is therefore not the most obvious one. An attempt at attributing the anisotropy of the auroral ionization to turbulence was undertaken by Booker, who first indicated (together with Gordon[80]) the possible role that turbulence may play in the occurrence of ionospheric inhomogeneities at the level of the E layer and above.

The ionized plasma becomes anisotropic in a magnetic field because the effective range of the electrons becomes restricted in the direction transverse to the magnetic field. The turbulence, as a result, also becomes anisotropic. The condition under which the control that the magnetic field exerts on the motion of the electrons (and ions) becomes a major factor is, according to Booker,[81] that the frequency of collision between the charged and neutral particles be appreciably less than their gyromagnetic frequency. For electrons in the atmosphere this takes place approximately above the 75 km level. Figure 26, taken from Booker's paper[81] shows the altitude dependence of the ratio of the average drift velocities of the electrons and ions in two mutually perpendicular directions (transverse and parallel to the field). The ratio of the horizontal and vertical dimensions of the electronic inhomogeneities is determined by two processes. First, directly by the collisions between the electrons and the molecules; the ratio of the horizontal to vertical dimensions of the inhomogeneities, proportional to the ratio of the drift velocities, is characterized in this case by the curve for the electrons in Fig. 26. Second,

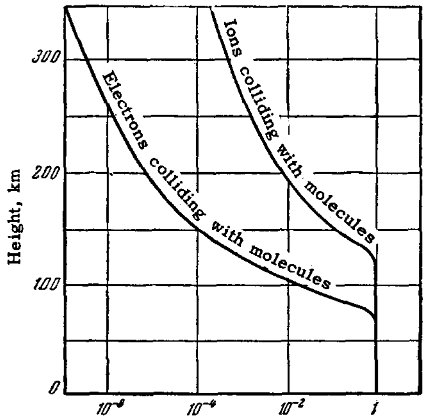


FIG. 26. Effect of collisions with neutral molecules on the drift velocity of electrons and ions in a magnetic field (after Booker[81]).

collisions between positive ions and molecules, since it is necessary to take into account the Coulomb attraction between ions and electrons. In the region of the E layer, the ratio of the transverse to longitudinal drift velocities for ions is close to unity, and therefore the Coulomb interaction of the ions and electrons will tend to reduce the anisotropy of the electron inhomogeneities. The limiting value of the anisotropy is given by the ion curve on Fig. 26. The resultant plot for the probable transverse dimensions of the electronic inhomogeneities is shown in Fig. 27. It can be seen that allowance for only the collisions between electrons and molecules should lead, for heights greater than 160 km, to inhomogeneity dimensions that are incompatible with the mean free path of the molecules (which determines the possible minimum turbulence scale).

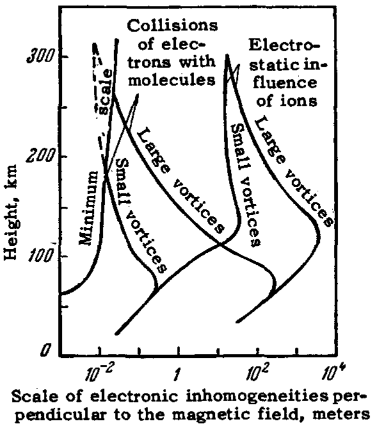


FIG. 27. Dimensions of electronic inhomogeneities as functions of the height and of the dimension of the vortices, with and without the electrostatic influence of the ions (after Booker[81]).

The vertical dimension of the electronic inhomogeneities is determined by the scale of the isotropic (in first approximation) turbulence of the neutral gas, for which Booker determines the limiting characteristic vortex dimensions. The upper limit L_1 is determined by the minimum energy of the vortex at a given level in the atmosphere, while the lower limit L_2 is determined from the condition that a turbulence scale less than L_2 is no longer possible in view of the presence of viscosity and the conversion of the kinetic energy of the vortex into heat.

For the level near 110 km, the characteristic dimensions of the vortices, according to Booker's calculations, range from $L_1 \cong 500$ m to $L_2 \cong 30$ m (Fig. 28). Booker does not investigate the turbulence spectrum.

In radar reflections one deals with backward scattering of the energy of the incident wave. The principal role in backward scattering, as shown by Booker and Gordon in a study of isotropic turbulence (and also by Ya. L. Al'pert[77]), should be played by small inhomogeneities, particularly with characteristic dimension $L \cong \lambda/4\pi$. For forward scattering at angles less than $\lambda/2\pi L_1$, it is important to take into account the large inhomogeneities with dimensions $L \cong L_1$. In the case of anisotropy, these conditions pertain to both longitudinal (L) and transverse (T) dimensions of the inhomogeneities.

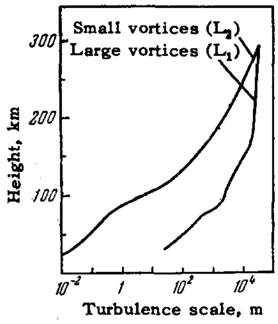


FIG. 28. Characteristic dimensions of vortices (turbulence scale) (after Booker[82]).

It is easy to see that for all the foregoing factors Booker's arguments are not specifically connected with the polar ionosphere, if we disregard the fact that the identification of longitudinal (relative to the magnetic field) turbulent motions with the vertical direction and of the transverse ones with the horizontal direction is valid only for sufficiently high latitudes. Therefore, according to Booker, the function of "auroral activity" in the formation of anisotropic ionospheric inhomogeneities reduces to the following:

a) The creation of conditions for the occurrence of increased electronic concentration and increased gradients of electron concentration, which can lead to an increase in the intensity of formation of electronic inhomogeneities.

b) The creation, along with geomagnetic effects, of unusually strong electric fields, which can cause the electronic inhomogeneities to drift with velocities necessary for the explanation of the fading and Doppler phenomena inherent in the radio reflections from polar aurorae. The role of the corpuscular agent, as suggested by Booker, can also be connected with these two factors.

Referring the reader to the original article[74,81] for the detailed calculations, we give here the final formula derived by Booker for the average coefficient of backward scattering in the case of an inhomogeneity field with characteristic dimensions L and T:

$$\sigma = (2\pi)^{3/2}\pi^2 \frac{1}{\lambda_N^4} \overline{\left(\frac{\Delta N}{N}\right)^2} T^2 L \exp\left(-\frac{8\pi^2 T^2}{\lambda^2}\right) \times \exp\left(-\frac{8\pi^2 L^2}{\lambda^2}\sin^2\psi\right), \tag{17}$$

where σ is the backward-scattering coefficient, i.e., the coefficient of scattering at angles close to 180°, λ_N is the critical wavelength for an electron density N, $\overline{(\Delta N/N)^2}$ is the mean square of the fluctuations of the electron density in the inhomogeneities, T is the transverse dimension of the inhomogeneities, L is the longitudinal dimension of the inhomogeneities, ψ is the angle between the direction of the radio beam and the longitudinal axis of the scattering inhomogeneity, and λ is the radar wavelength. A formula quite similar to (17) was obtained independently by Ya. L. Al'pert.[77]

Integration of (17) over the proposed scattering volume enabled Booker to estimate the values of the reflected energy. He found it possible here to evaluate separately the longitudinal dimensions of the inhomogeneities, since the calculations could be carried out in such a way that the integral expression contained a factor that depended on L and on the angle of reflection, which in turn determined the "aspect sensitivity." According to Booker's calculations,[74] the characteristic longitudinal dimension of the auroral inhomogeneities is on the order of 7 meters. The transverse dimension of the inhomogeneities, extimated in the paper quite crudely (on the basis of the observed limiting frequency of the auroral radio reflections) is found to be on the order of 0.16 meter. The ratio ($0.16:7 \cong 2 \times 10^{-2}$) agrees with the values predicted by Booker's theory (see Fig. 26) for heights on the order of 110 — 120 km. One might assume that the uncertainty both in the initial data and in the premises of the theory is so great that no particular significance should be attached to this coincidence. However, order-of-magnitude estimates of the inhomogeneities by simpler means, carried out by some authors (Collins and Forsyth[64] by investigating fading in separated receivers, McNamara[75] and Kaiser[41] by taking account of deviations from the angle of specular reflection), although differing from the values given by Booker, remain within the same order of magnitude. Ya. L. Al'pert,[77] in an analysis of the results of Bailey et al., also estimates the dimensions of the inhomogeneities in the lower ionosphere at approximately 5 — 8 meters. Apparently the vertical dimension of the auroral inhomogeneities should actually not be greater than about 10 meters, and accordingly the average transverse dimensions of the inhomogeneities are on the order of a meter.

The Booker scheme is open to criticism in many respects. Thus, for example, Booker assumes somewhat arbitrarily an electron concentration in the inhomogeneities on the order of $N \cong 10^6$ cm^{-3}. Taking account of the strength of the reflected signal and the probable dimensions of the scattering region, he obtains for the mean square of the fluctuations a value $\overline{(\Delta N/N)^2} = 10^{-7} - 10^{-6}$. Al'pert's calculations[77] for conditions of a much less distrubed ionosphere lead to values that are two or three orders of magnitude greater. Booker uses as a spatial characteristic of the turbulence an autocorrelation function of the form

$$\varrho = \exp\left(-\frac{r^2}{L^2}\right), \tag{18}$$

where L is the turbulence scale and r the distance between two points. The reasons for choosing precisely this function are not stated in Booker's article (see references 77 and 83). For all this, the great merit of Booker's work in the interpretation of the observed radio reflections from polar aurorae is the attempt to advance from qualitative and physically vague estimates to a quantitative evaluation of the results of the observations. Perhaps not all of Booker's original premises may prove to be true; it is possible that the anisotropic turbulence alone is not sufficient to explain the anisotropy in the ionization in the polar regions. But the existence of even a tentative working hypothesis is useful in stimulating research and the subsequent development of more correct ideas of the specific nature of the phenomenon.

To conclude this section, devoted to attempts at interpreting radar observations of polar aurorae, it is useful to dwell on a comparison of the results with certain optical data. The latter, which yield extensive data on the excitation processes in polar aurorae, will yield in some cases definite information on the ionization, too. The reliability and unambiguity of these data is directly dependent, naturally, on the degree of correlation of the two phenomena. As already noted, this correlation is not subject to doubt on a large space-time scale, but is very unreliable in details.

Let us mention two optical investigations pertaining to the question of interest to us.

Photometry of the emission from the ionized nitrogen molecule in polar aurorae (the first negative system N_2^+, transition $B^2\Pi \rightarrow X^2\Sigma$) leads to sufficiently reliable estimates of both the average intensity and the maximum values that correspond to very bright aurorae. On the basis of spectroscopic data by Vegarde and Kvifte,[84] Seaton[85] assumes an average value of 5×10^{11} photons per second for the emission of photons from the zero band ($\lambda = 3914$ A) of this system, in a column of atmosphere of 1 cm^2 cross section. Then the total photon emission when all bands of the negative system N_2^+ are excited, should be estimated at approximately twice the λ 3914 and five times the λ 4278 emission. If it is true that the N_2^+ molecules are excited in polar aurorae directly, in a single act together with the ionization of the N_2 molecule, then the number of emitted photons should be not less than the number of produced electrons.

The equation

$$\frac{dN}{dt} = a\eta(N_2^+) - \alpha_{\text{rec}}N^2 \tag{19}$$

can be used to estimate N — the electron concentration [here $\eta(N_2^+)$ denotes the number of photons in the system $B^2\Pi \rightarrow X^2\Sigma$, emitted in one cm^3 of the glowing auroral volume, proportional to the number of electrons formed there; a is a proportionality coefficient and α_{rec} is the recombination coefficient]. Putting $dN/dt = 0$ and $\alpha_{\text{rec}} \cong 10^{-8}$ cm^3/sec, we can find N, for which we must also know a and $\eta(N_2^+)$. If $\Pi(N_2^+)$ is the total photon emission per second from the $B^2\Pi - X^2\Sigma$ system in a 1-cm^2 column, then

$$\eta(N_2^+) = \frac{\Pi(N_2^+)}{l}, \tag{20}$$

where l is the vertical dimension of the glow volume. Taking sensible values for a and l ($a \geq 1$, $l = 1$ km), Seaton obtains for the electron density a value $N \geq 2 \times 10^7$ cm^{-3}. The result agrees with the estimates of the electron density based on the assumption of critical (total) reflection of radar signals.

Just the opposite is concluded by Omholt.[86] He uses the following photometric data (which do not differ greatly from those of Seaton) for the λ 4278 emission of the first negative system of nitrogen, namely $(2-10) \times 10^{10}$ photons per second in a 1-cm^2 atmosphere column for moderate and strong aurorae, and approximately 4×10^{11} photons for the aurorae of maximum strength. In simultaneous observations of the critical frequency of the reflections from the "auroral" sporadic E_a layer and of the intensity of the λ 4278 emission of N_2^+, Omholt obtained a rather good correlation between the two. Since the interval of the critical frequencies in vertical reflections range in these measurements from 4 to 9 Mc, Omholt assumes for the "auroral" ionization probable values from 2×10^5 to 10×10^5 cm^{-3}, and on this basis he gives preference to the mechanism of partial reflection.

CONCLUSION

We have considered the experimental data obtained in observations of radio reflections from polar aurorae at UHF frequencies, and attempts at interpretations of these data. The greater part of the observational material obtained to date was obtained by means of relatively simple radar apparatus and techniques. These were used to explain certain main regularities of the phenomenon, and to determine its connection with other geophysical processes at high latitudes. The establishment of more accurate characteristics and physical parameters entails considerable difficulties with the existing (more accurately, with the employed) techniques. The obvious need for obtaining more accurate and more detailed information makes it advisable to employ at present more specialized procedures in these investigations and more highly perfected apparatus, to increase the directivity of antennas, to increase the sensitivity of the receivers, to vary the distance between the transmitting and receiving points, etc.

As in any other field of physical experimentation, the observations become most valuable if they are explained by means of a sufficiently clear theory or a suitable working hypothesis. In radio investigations of the polar aurora, during the first stages of disclosure of the general regularities, the leading theory was the geometrical reflection scheme of Chapman. At the present time, in processing the ever increasing volume of data, a need is felt for a theory which would interpret physically the picture of radio wave reflection from regions of anomalous, increased ionization in the polar regions. With completion of the IGY, the number of stations carrying out research on radio reflections from polar aurorae has been reduced somewhat. But this can be compensated for by using new apparatus and more flexible specialized procedures in the remaining stations. Both geophysics and the practice of ionospheric service at high latitudes have already gained much use from these observations. Their development and improvement, as well as the use of the data already accumulated, should obviously contribute to a better understanding of the varied interrelated processes that abound in the upper layers of the atmosphere at high latitudes.

Note added in proof. Publication of materials on the radio observation of polar aurorae, and particularly of the results of IGY, is proceeding presently at a rapid rate. Being unable to include most of the new papers published after the writing of this article in the cited bibliography, we consider it useful to refer our readers to the journals J. Geophys. Res. 65, No. 8, August 1960 and to J. Atmos. Terr. Phys. 19, No. 1, September 1960, which contain between them five original papers on this subject. A survey article has also been written by Booker for the book "Physics of the Upper Atmosphere" (J. A. Ratcliffe, editor, London, 1960). Noteworthy in this article is Booker's remark on the variation of the character of back scatter with height, deduced from certain new observations. Booker proposes that it may be necessary to take this theoretically into account by further refinement of the type of the autocorrelation function. It should be pointed out, incidentally, that the original Booker-Gordon theory made use of an autocorrelation function other than the Gaussian one later employed by Booker. The errors connected with the use of a non-Gaussian function are pointed out by Al'pert in the article referred to in our survey.

---

[1] L. Harang and W. Stoffregen, Hochfrequenztechnik und Elektroakustik **55**, 105 (1940).

[2] R. K. Moore, J. Geophys. Res. **56**, 97 (1951).

[3] A. M. Peterson and R. L. Leadabrand, J. Geophys. Res. **59**, 306 (1954); Peterson, Villard, Leadabrand, and Gallacher, J. Geophys. Res. **60**, 492 (1955).

[4] S. Stein, J. Geophys. Res. **63**, 391 (1958).

[5] Dyce, Dolphin, Leadabrand, and Long, J. Geophys. Res. **64**, 1815 (1959).

[6] J. Nakata, Repts. Ionosph. Res. in Japan **12**, 1 (1958).

[7] Bailey, Bateman, and Kirby, Proc. IRE **43**, 1181 (1955).

[8] Ya. G. Birfel'd, Izv. Akad. Nauk SSSR, Ser. Geofiz. No. 12, 1871 (1960).

[9] S. K. Mitra, The Upper Atmosphere, Univ. of Calcutta, 1952.

[10] Al'pert, Dobryakova, Chudesenko, and Shapiro, Usp. Fiz. Nauk **65**, 161 (1958).

[11] Ya. L. Al'pert, Usp. Fiz. Nauk **71**, 369 (1960), Soviet Phys.-Uspekhi **3**, 479 (1961).

[12] "Rocket Investigations of the Upper Atmosphere" (Russ. Transl.) IL, 1957.

[13] K. I. Gringauz, Doklady Akad. Nauk SSSR **120**, 1234 (1958) and **131**, 1301 (1960), Soviet Phys.-Doklady **3**, 620 (1959) and **5**, 361 (1960).

[14] Lovell, Clegg, and Ellyett, Nature **160**, 372 (1947).

[15] N. Herlofson, Nature **160**, 867 (1947).

[16] A. Aspinol and G. S. Hawkins, J. Brit. Astron. Assoc. **60**, 130 (1950).

[17] Forsyth, Petrie, Vawter, and Currie, Nature **165**, 561 (1950).

[18] G. Hellgren and J. Meos, Tellus **4**, 249 (1952).

[19] Currie, Forsyth, and Vawter, J. Geophys. Res. **58**, 179 (1953).

[20] A. G. McNamara and B. Currie, J. Geophys. Res. **59**, 279 (1954).

[21] V. Bullough and T. R. Kaiser, J. Atmos. and Terr. Phys. **5**, 189 (1954); **6**, 98 (1955).

[22] L. Harang and B. Landmark, J. Atmos. and Terr. Phys. **4**, 322 (1954).

[23] R. B. Dyce, J. Geophys. Res. **60**, 317 (1955).

[24] Ya. G. Birfel'd, Izv. Akad. Nauk SSSR, Ser. Geofiz. No. 4, 543 (1957).

[25] D. W. R. McKinley and P. M. Millman, Canad. J. Phys. **31**, 171 (1953).

[26] R. S. Unwin, Ann. Geophys. **15**, 378 (1959).

[27] R. S. Unwin, J. Geophys. Res. **63**, 501 (1958).

[28] M. Gadsden, Ann. Geophys. **15**, 404 (1959).

[29] G. F. Lyon, Canad. J. Phys. **38**, 385 (1960).

[30] V. I. Pogorelov, Izv. Akad. Nauk SSSR, Ser. Geofiz. No. 8, 1949 (1958).

[31] B. E. Brunelli and S. M. Sandulenko, Информационный бюллетень Советской Антарктической экспедиции, (Information Bull. of the Soviet Antarctic Expedition), No. 13, 29 (1959).

[32] Booker, Gartlein, and Nickols, J. Geophys. Res. **60**, 1 (1955).

[33] P. A. Forsyth, Canad. J. Phys. **38**, 593 (1960).

[34] Presnell, Leadabrand, Peterson, Dyce, Schlobohm, and Berg, J. Geophys. Res. **64**, 1179 (1959).

[35] C. Störmer, The Polar Aurora, Pergamon Press, 1955.

[36] V. I. Dovger, Проблемы Арктики и Антарктики, (Problems of Arctic and Antarctic), No. 2, 119 (1960).

[37] R. S. Unwin and M. Gadsden, Nature **180**, 1469 (1957).

[38] S. Chapman, J. Atmos. and Terr. Phys. **3**, 1 (1953); J. Chain, J. Geophys. Res. **58**, 377 (1953).

[39] A. P. Nikol'skii, Magnetic Disturbances in the Arctic, Trudy, Arctic Research Institute, **36**, 1951.

[40] M. S. Bobrov, Астрономический журнал **36**, 1029 (1959), Soviet Astronomy **3**, 943 (1960).

[41] T. R. Kaiser, The Airglow and the Aurora, N.Y., Pergamon Press, 1955.

[42] A. I. Grachev, Спектральные, электрофотометрические и радиолокационные исследования полярных сияний и свечения ночного неба, (Spectral, Electrophotometric, and Radar Investigation of Polar Aurorae and of the Glow of the Night Sky), AN SSSR, Coll. No. 2-3, 19 (1960).

[43] Fricker, Ingalls, Stone, and Wang, J. Geophys. Res. **62**, 527 (1957).

[44] Ya. G. Birfel'd, op. cit. ref. 42, No. 2-3, 15 (1960).

[45] J. H. Meek and A. G. McNamara, Canad. J. Phys. **32**, 326 (1954).

[46] Bullough, Davidson, Kaiser, and Watkins, J. Atmos. and Terr. Phys. **11**, 137 (1957).

[47] V. I. Pogorelov, op. cit. ref. 42, No. 2-3, 28 (1960).

[48] V. I. Yarin, op. cit. ref. 42, No. 2-3, 37 (1960).

[49] N. Gadsden, Ann. Geophys. **15**, 396 (1959).

[50] B. K. Bhattacharyya, Canad. J. Phys. **38**, 624 (1960).

[51] D. R. Harrison and C. D. Watkins, Nature **182**, 43 (1958).

[52] V. I. Pogorelov, Izv. Akad. Nauk SSSR, Ser. Geofiz., No. 7, 1082 (1960).

[53] J. N. Abbott, Canad. J. Phys. **36**, 643 (1958).

[54] R. A. Zevakina and Z. Ts. Rappoport, Trans. All-Union Inter-University Conference on Radiophysical Methods of Ionospheric Research, Trudy Siberian Physico-Technical Inst., No. 37 (1959).

[55] V. M. Driatskii and A. S. Besprozvannaya, Геофизические исследования в Советской Арктике, (Geophysical Research in the Soviet Arctic), No. 3, 98 (1960).

[56] R. Penndorf and S. C. Coroniti, J. Geophys. Res. **63**, 789 (1958).

[57] Ya. I. Fel'dshteĭn, Исследования полярных сияний, (Investigation of Polar Aurorae), AN SSSR, Coll. No. 4, 61 (1960).

[58] E. K. Smith and J. W. Tinney, J. Geophys. Res. **65**, 885 (1960).

[59] R. W. Knecht, J. Geophys. Res. **61**, 59 (1956).

[60] F. Ya. Zaborshchikov and N. I. Fedkina, Проблемы Арктики, (Problems of the Arctic), No. 2, 149 (1957).

[61] James, Bird, Ingalls, Stone, Day, Lockwood, and Presnell, Nature **185**, 510 (1960).

[62] Little, Rayton, and Roof, Proc. IRE **44**, 992 (1956).

[63] P. A. Forsyth and E. L. Vogan, J. Atmos. and Terr. Phys. **10**, 215 (1957).

[64] C. Collins and P. A. Forsyth, J. Atmos. and Terr. Phys. **13**, 315 (1959).

[65] Forsyth, Green, and Mah, Canad. J. Phys. **38**, 6 (1960).

[66] J. Paton, J. Brit. Astron. Assoc. **64**, 376 (1954).

[67] M. A. Ellison and J. Paton, Observatory **74**, 246 (1954).

[68] Egeland, Hultquist, and Ortner, Nature **185**, 519 (1960).

[69] P. Glöde, Radio und Fernsehen **8**, 415 (1959).

[70] S. Chapman and C. G. Little, J. Atmos. and Terr. Phys. **10**, 20 (1957).

[71] T. J. Seed, J. Geophys. Res. **63**, 517 (1958).

[72] T. R. Kaiser, J. Geophys. Res. **62**, 297 (1957).

[73] J. R. Mentzer, Diffraction and Scattering of Radio Waves (Russ. Transl.), Soviet Radio Press, 1958.

[74] H. G. Booker, J. Atmos. and Terr. Phys. **8**, 204 (1956).

[75] A. G. McNamara, Canad. J. Phys. **38**, 424 (1960).

[76] Ya. L. Al'pert, Usp. Fiz. Nauk **34**, 262 (1948); **38**, 30 (1949); **49**, 49 (1953).

[77] Ya. L. Al'pert, ibid. **61**, 424 (1957).

[78] Ya. L. Al'pert, Исследования ионосферы и метеоров, (Investigations of the Ionosphere and of Meteors), AN SSSR, Coll. No. 2, 7 (1960).

[79] Ya. L. Al'pert and A. A. Aĭnberg, JETP **21**, 389 (1951).

[80] H. G. Booker and W. Gordon, Proc. IRE, **38**, 401 (1950).

[81] H. G. Booker, J. Geophys. Res. **61**, 673 (1956).

[82] Bayley, Bateman, Berkner, Booker, Montgomery Purcell, Salisbury, and Wiesner, Phys. Rev. **86**, 141 (1952).

[83] V. I. Tatarskii, Теория флуктуационных явлений при распространении волн в турбулентной атмосфере, (Theory of Fluctuations in the Propagation of Radio Waves in the Turbulent Atmosphere) AN SSSR, 1959.

Translated by J. G. Adashko