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Altitude Characteristics of Radar Aurora as Seen by a 90-MHz Double-Altitude Radar System Operated at Karmaselga, Karelia

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Abstract. This paper presents the first results of measurements of radar auroral altitude and thickness obtained with a 90-MHz double-altitude radar (DAR system) installed at Karmaselga (63° N, 34° E). The system is a development of the sea surface interferometer technique used by Unwin and Gadsden (1957). It provides altitude measurements with an accuracy of about 1.5 km. The altitude characteristics are studied for two selected events in connection with other geophysical data. The results of this study include the following findings: (1) the variability of the radar auroral altitude is significantly greater within the westward than in the eastward electrojet; (2) the systematic difference of auroral echo altitude observed between the eastern and western azimuths (east-western altitude asymmetry) generally has the same sign and value within both electrojets; (3) the occurrence of a double-layer altitude structure of the auroral echo with a layer thickness of about 2 km and an altitude difference of less than 10 km together with a life-time of less than 1 min is a unique feature of the observations. An eastward altitude inclination of individual current structure of the auroral electrojets is discussed as a source of the observed east-western asymmetry in addition to similar sources known before. A mechanism of collective interaction of auroral electron fluxes with the E-region ionospheric plasma is discussed in the interpretation of the observed double-layer structure.

Key Words: Radar auroral altitudes – Vertical interferometer – East-western altitude asymmetry – Double-layer altitude structure – Altitude inclination of current layers – Electron-beam-plasma interaction

Introduction

A new 90-MHz double-radar system (DAR) designed for studying altitude and thickness of the radar aurora in connection with auroral substorm processes has been in operation in Northern Karelia since February 1979. The DAR has been constructed as a part of the ground-based program for the International Magnetospheric Study. This paper describes the original investigation methods, the equipment, and the first results obtained by the DAR in February 1979.

Altitude and thickness of layers of VHF auroral irregularities are rather unknown from past radar auroral investigations. Not more than ten papers have been devoted to this question over the 30-years study of this subject. Particularly, radar auroral altitude data obtained simultaneously with a combination of ground-based observations are lacking. According to our opinion a complex approach to this problem will make possible a further progress of the present understanding of both radar auroral and other substorm phenomena. In this connection, the investigation of the following features of radar auroral altitude characteristics are of interest:

– their difference within westward and eastward electrojets;
– their correlation with altitude and thickness of auroral forms and Es-layers;
– their peculiarities near foot-points of field-aligned currents;
– their dynamics in connection with variations of the electron energy flux and the value of ionospheric electric fields.

An analysis of special radar auroral problems, is also possible, such as:

– the origin of the observed east-western asymmetry of the auroral echo altitudes;
– the local distribution of altitudes within the area occupied by radar aurora;
– the origin of the radar auroral altitude lamination, which was discovered during the first DAR observations and the peculiarities of geophysical phenomena associated with it.

Description of the Experiment

The radar is located near the village of Kalmaselga (63° N, 34° E). The geographic location of the radar opens the possibility to observe auroral echoes under favorable aspect angles over observatories installed by the Polar Geophysical Institute (PGI) and partially over observatories in northern European countries. Aspect-angle contours calculated for 110 km height on the basis of the International Geomagnetic Reference Field 1975 are presented in Fig. 1. The DAR system is located on the steep southern bank of the Segozero lake. The water surface of the lake provides an excellent flat reflector of radio waves practically within the total sector of observations shown in Fig. 1.

Methods of Measurement and Interpretation

The DAR method of measuring was developed on the basis of the classical method by Unwin and Gadsden (1957). According to their method the height of scattering layers is determined by measuring the slant range location of each of the multiple narrow-beam elevation lobes. However, in their method a single-valued measurement of the radar auroral altitude is possible only for scattering layers extended from a certain slant range to the radar horizon. The principal difference between the classical method and the DAR method is the application of an additional interferometer with a vertical base twofold shorter than

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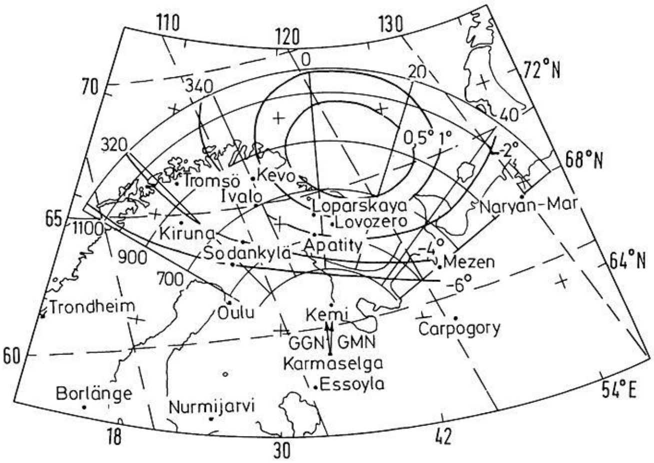

Fig. 1. The map of Scandinavia and Kola Peninsula with the coverage zone of DAR and geographical location of observatories relative to the radar. GMN and GGN – directions of local geomagnetic and geographic meridians near the radar. The grid of corrected geomagnetic coordinates is shown by dotted lines. The difference between right angle and usual aspect angle value is given by digits near the aspect-angle contours

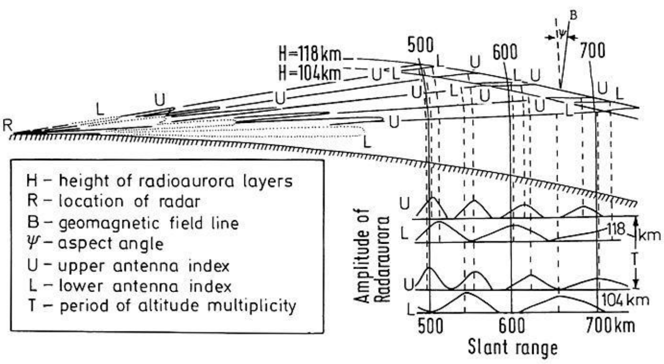

Fig. 2. Scheme of the DAR method. Amplitude-range picture of the main interferometer (U-index) is the same for 104- and 118-km radar auroral altitude, at least; within a 500–600 km slant range interval there is an altitude multiplicity. In contrast, an additional interferometer (index L) gives quite different auroral echo display for the same two altitude values. Comparative analysis of upper and lower interferometer displays eliminates the ambiguity

that of the main interferometer. This provides unique measurements of the altitude of radar auroral areas independently of their location relative to the radar horizon. The unique, i.e. single-valued, measurements in this case are possible only within a certain altitude range (so called period of the altitude multiplicity) outside which the altitude is a multiple-valued function of the slant range location of the elevation lobes. Moreover, our method requires that the radar auroral area have a slant range size not less than a certain minimum value (so-called minimum size).

The interferometer with the large base (upper or main interferometer) shows maximum accuracy of measurement but has a short period of altitude multiplicity. The lower or additional interferometer, on the contrary, provides unique measurements in a wider range of altitudes but shows less accuracy of measurement. Figure 2 explains the principle of measuring with two interferometers.

The value of the period of altitude multiplicity depends on the slant range. For example, the period for the upper and lower interferometers amounts to 12 and 20 km for 500 km slant range and to 26 and 44 km for 1,000 km, respectively. Its value, depending on the slant range, is given by solid lines in Fig. 3a. Apparently, the possibility of single-valued altitude measurements exists in the altitude range of 100 to 120 km at small slant range values, and in the altitude range of 90 to 130 km near the radar horizon. Our measurements are possible only when the slant range size of the radar auroral area is not less than the slant range distance between two neighboring elevation lobes. Thus, for the mean 110-km height the values of the minimum size of the radar auroral area are 70 and 100 km for a 500-km slant range and 130 and 200 for 1,000 km, for the upper and lower interferometers, respectively. The dependence of the minimum size value on the slant range is also given in Fig. 3a, by dotted lines. It is impossible to measure the altitude characteristics of the spatially localized radar aurora by means of the DAR system. For practical purposes, this limitation affects only the B_2 type (IAGA classification, 1968) of the auroral scatter.

The thickness of the radar auroral layer is a monotonic function of the ratio of the signal intensity at a maximum value to that at a minimum value of the elevation lobe. We computed the dependence of this function on the slant range for a set of thickness values of the homogeneous layers of scatter. Radar auroral thickness was estimated by selecting parameters of the calculated curve that were closest to the experimental curve.

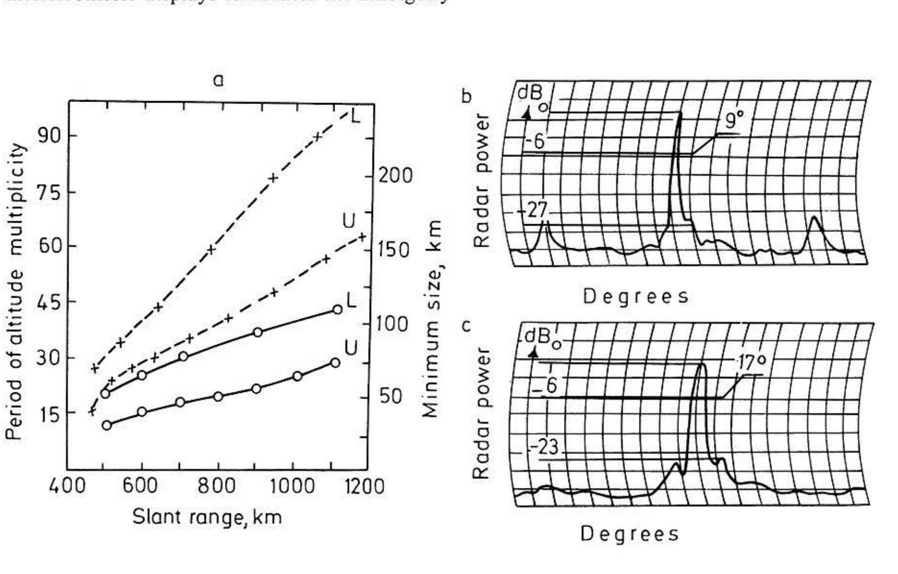

Fig. 3. a Calculated curves of the period of altitude multiplicity (*solid line*) and minimum slant range size of radar auroral area (*dotted lines*) subject to slant range; U- and L-indexes correspond to upper and lower interferometers. Curves are given for average altitude value equal to 110 km. **b, c** The experimental patterns of direction of the antennas in a horizontal surface for lower (Fig. 3b) and upper (Fig. 3c) interferometers. The beam width of the main horizontal lobe is shown in degress at level 6 dB since one and the same antenna was used for transmitting and receiving

Each interferometer has horizontal antenna polarization. The multilobes elevation antenna directional pattern is formed far from the radar, owing to radiowave reflection from the water surface. Because the reflection surface is perfectly flat, this pattern may be computed with the necessary accuracy. The antenna radiator height above the lake surface necessary for calculation was measured by transit theodolite. The interferometer base is known to be twice as large as the radiator height. The base values obtained were 39 and 26 times the mean radar wavelengths for the upper and lower interferometers, respectively. The analysis of the results of numerous base value determinations showed an error not exceeding 0.5 m. Since this value is much less than the base values, its influence on the accuracy of altitude measurements may be neglected.

Both interferometers can be used in a circular azimuth scan mode as well as with a constant observation azimuth. During the first observation period (7–16 February, 1979) the lower interferometer was used in the azimuth scan mode. The upper interferometer was directed at various azimuths by an assistant. Two kinds of indicators were available, namely plane position intensity (PPI) and amplitude range, for the lower and upper interferometers, respectively. Photoaccumulation was applied to increase the signal-to-noise ratio of the amplitude indicator. Thus each amplitude frame represents the statistical average of 325 individual realizations. This procedure minimized additional errors associated with the signal amplitude stochasticity. The two types of indicators supplement each other. The amplitude indicator provides the maximum accuracy for measurements of the altitude characteristics, but only with constant azimuth. The second indicator gives information about auroral echo altitudes with less accuracy but nearly simultaneously for all azimuths. The availability of PPI is convenient for analyzing the radar results together with other geophysical data and also for excluding the multiplicity of amplitude frames associated with the finite width of the horizontal directional pattern of the upper antenna. This pattern is shown in Fig. 3c.

Thus far methods described above have been discussed as applied to the model of an one-layer altitude structure of the radar auroral. However, the very first observations showed that although seldom the auroral echo also appeared in double layer form. Therefore, it is necessary to describe the possibilities of the DAR system for observing such structures. To begin with, the behavior of altitudes dependent on slant range may be resolved for all sections if there are several radar auroral layers with slant range sizes more than the minimal size and they are situated in different slant range sections at different heights. The presence of many signal amplitude extrema corresponding to various altitudes at one and the same slant range section of the amplitude indicator is necessary but not sufficient to indicate a multilayer altitude structure of the radar aurora. Two basic false situations must be eliminated to arrive at a unique conclusion. The first is the simultaneous registration of radar auroral signals from several different azimuths owing to the finite width of the horizontal antenna directional pattern. The second situation is the formation of false extrema of the signal amplitude owing to an abrupt signal inhomogeneity dependent on slant range. For example, the presence of an intensive, spatially localized radar auroral signal of the B_2 type at the slant range near the maximum of elevation lobe gives a double maximum, i.e., falsely indicates a double-layer altitude structure. The first false situation can be eliminated by selecting radar auroral areas with small azimuth sizes and homogeneous distribution of the inner azimuth intensity. The criterion of small azimuth size will be given below. The second false situation can be eliminated by selecting only regularized amplitude frames, i.e., by having a certain order of disposition of lobe extrema which corresponds to different altitudes of scatter. One and the same sign and value of the shift of the lobe maxima and minima serve as main criterion of regularity. Frequently the abrupt inhomogeneity of the radar auroral signal dependent on the slant range may be easily distinguished from multilayer structure by the difference between the form of signal amplitude splash and the form of the elevation lobe. Examples of different cases will be cited when the double-layer altitude structure is described.

Accuracy and Resolving Ability

The total instrumental error of slant range measurements with due regard for the radar pulse width, the screen size, the electron tube focus quality is 2–3 km depending on the slant range value. This leads to an error in height measurement of not more than 0.5 km for the whole slant range interval. The reading error associated with both the finite width of the elevation lobe and the minimum scale value of the amplitude indicator amounts to about 5 km. Thus the maximum error of radar auroral altitude measurements accounting for all the above described parameters of the instruments, reaches 1.5 km. This value refers only to the measurement of the upper interferometer. The accuracy of measurement by the lower interferometer is in addition influenced by the form of the amplitude-range profile of the radar auroral signal. This form remains unknown with use of the intensity indicator, and consequently the exact accuracy of measurement cannot be determined. However, by comparing the measurements made by both interferometers we estimated it at 2.5–3 km. The accuracy of the thickness measurements were estimated with computer modeling of scatter, using a set of thickness model parameters that has a step equal to 2.5 km. The accuracy of the thickness measurement is then almost the same as that of an altitude measurement, namely about 2.5 km. Often we are unable to realize this accuracy because of sharp changes in radar auroral signal amplitude as a function of slant range.

In connection with the discovery of the double-layer altitude structure of the radar aurora, resolving ability of the system was estimated by computer modeling of the scatter process. Two neighboring lobes were assumed to be resolved separately if the signal value between them declined to one-fifth of the maximum value. The minimum altitude difference of radar auroral layers needed for such a reduction was defined as the estimated resolving ability. Computer calculations showed that resolving ability decreased with the increase of slant range, approximately from 3–5 km at minimal slant range values up to 9–11 km near the radar horizon.

Calculation of the Tropospheric Refraction

The geographic location of the DAR system allows us to observe the radar aurora over the main PGI observatories at minimum slant range values of about 500–600 km. Thus the standard tropospheric refraction increases the measured altitude values by not more than 2–3 km. For slant range values of 700–900 km the standard refraction contribution is usually set at 4–6 km (see, for example, Leadabrand et al., 1965). Statistical methods are used to calculate the standard refraction on the basis of average values of the tropospheric parameters. At any specific moment the presence of irregular tropospheric refraction interferes with calculation of the absolute value of the radar auroral altitude. But it does not prevent investigation of the behavior of the radar auroral altitude characteristics in relation to sub-

Table 1

DAR technical parameters	Upper interferometer	Lower interferometer
Transmitted frequency (MHz)	88±5	88±5
Transmitted peak power (KW)	75	75
Pulse width (μs)	8	8
Vertical base (Wave length)	39	26
Receiver sensitivity (dB/w)	140	140
Beam width of the antennas directional pattern on a horizontal surface (0.5 level) (deg)	17°	9°
Side lobe level (dB)	25	30
Antenna gain relative to dipole (dB)	15	20
Rotating period (s)	80	72
Pulse repetition frequency (Hz)	50	50

storm processes; this is possible independently of any refraction. Indeed, the time scale of the auroral substorm processes with due regard to its microstructure, does not exceed a few minutes. In contrast, the value of the irregular refraction, determined by temperature and humidity height-integrated over a 10-km tropospheric layer, changes much more slowly. According to Arora and Wait (1978) the characteristic time scale of such changes comprises approximately one day.

Equipment

Both interferometers have a set of horizontally located multielement Yagi-antennas, fed in-phase. There are four antennas with ten elements and six with five elements for the upper and lower interferometers, respectively. Antenna aperture sizes for the former and the latter are 9.5 and 17.5 m, respectively. Experimental horizontal antenna direction patterns are given in Fig. 3b and c. Other antenna parameters are presented in Table 1.

The DAR consists of two identical radars with slightly different frequencies. The difference is very small but not less than 0.7 MHz. Both radars have a common arrangement for feeding synchronization, and indication. For the amplitude-range indicator a variable time delay is provided for the scan. The delay may be changed in 50-km steps over a range of 0–500 km. The delay value is chosen by the operator according to the existing picture of PPI. Both screen pictures are photographed together with slant range and azimuth scale marks. The amplitude-range photos are made every 6.5 s, the PPI photos each rotation period of the antenna. The main radar parameters are given in Table 1. The scheme of the experimental arrangement is given in Fig. 4a.

Observations and Results

The total observation time of radar aurora by DAR amounted to about 40 h from February 7 to 16. These periods are shown by black rectangles in Fig. 4b. A concise representation of the data from the Loparskaya magnetometer is given in the same figure. In this paper we shall consider only two substorm events (11–12 and 15 February, 1979). Both of them correspond to the maximum of auroral electrojet intensity for the whole period of observation. The first corresponds to the westward electrojet (about 02.30 MLT), the second, to the eastward electrojet (about 18.40 MLT). Magnetometer data from Loparskaya and Apatity for these events are given in Fig. 5. Riometer data from Loparskaya on the most interesting 11–12 February event are also

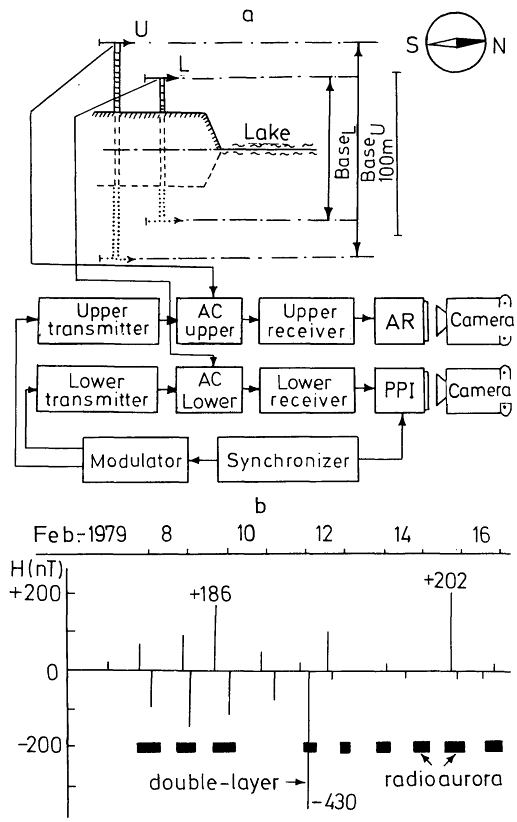

Fig. 4. a Schemes of apparatus: block intercommunication and mirror reflection of antenna. **b** Short chart for data from both the Loparskaya magnetometer and DAR radar during February 1979. Maximum variations of magnetometer for each day are given by vertical lines. Three of the most intense substorms are numbered according to their size

given. The following dependencies will be considered for these events:

– the dependence of the radar auroral altitude on slant range at each individual azimuth of observation. For the azimuths close to 350° this dependence gives information about altitude change with geomagnetic latitude;

– the dependence of the auroral echo altitude as averaged over azimuth on the slant range within the radar view;

– the dependence of radar auroral altitude on the azimuth of observation at constant slant range values. In the western section of the radar view such dependence means the dependence of the altitude of scatter on the geomagnetic longitude. The parameters of radar auroral thickness for both events and the double-layer altitude sturcture will also be considered.

Data processing and methods of eliminating the multiplicity of measurements will be illustrated first. Figure 6 presents an example of (a) a PPI map of radar aurora as observed with the lower interferometer; (b) an example of the simultaneous amplitude range profile of the radar auroral signal along a 347° azimuth as observed with the upper interferometer; and (c) an example of calculated curves of the location of the elevation lobe for both interferometers in the slant range coordinates. The curves for the upper and lower interferometer are represented by solid and dashed lines, respectively. The analogous curves for location of elevation lobe minima should have been placed in the middle of two neighboring maxima curves. The former is not shown for the sake of simplicity. The signal extrema of the upper interferometer taken from Fig. 6b are plotted on

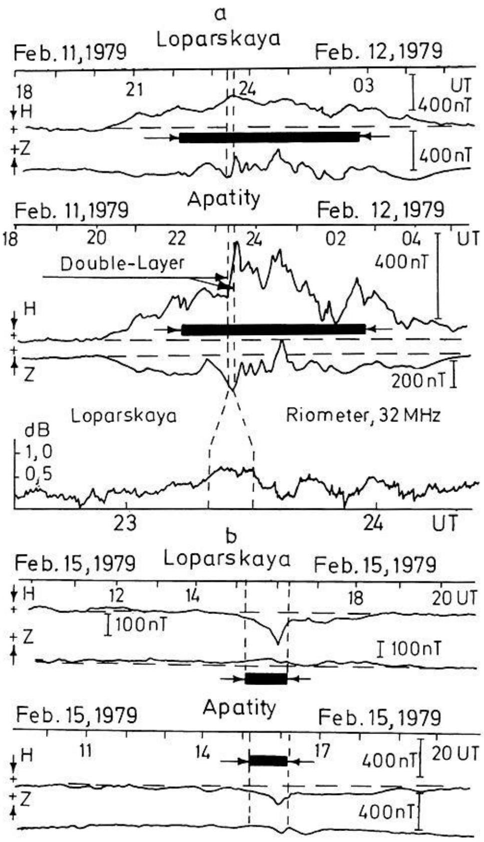

Fig. 5. Data of Loparskaya and Apatity magnetometers along with data of radar auroral altitude characteristics determined by the DAR system for February 11–12 and 15 events. Periods of measurements of radar auroral altitude are marked by *black rectangles*. Two moments of double-layer altitude structure of scattering are marked by *vertical dotted lines* near the maxima of both magnetometer variations and riometer bay

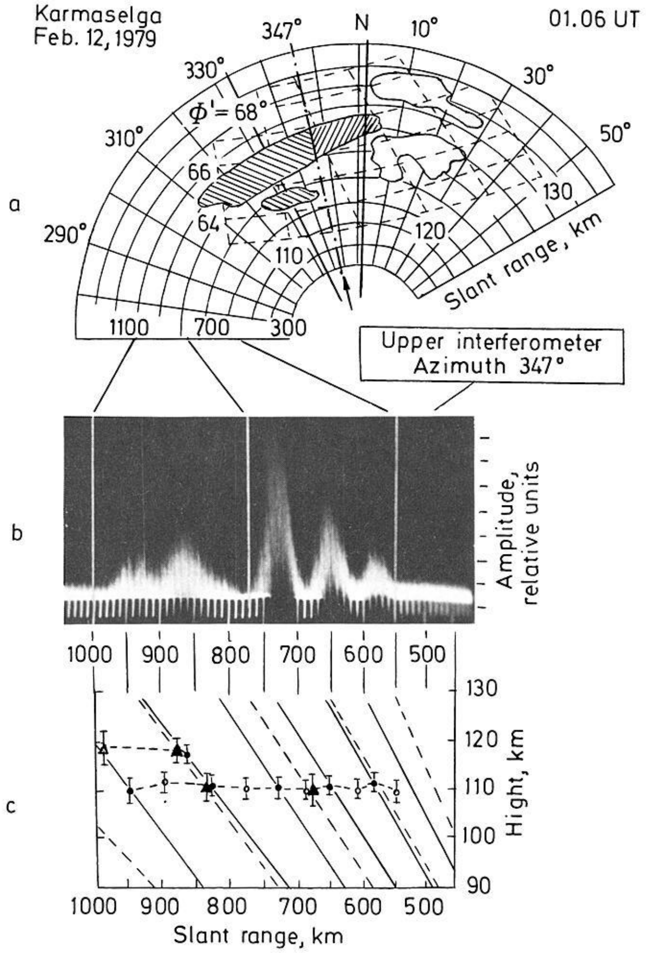

Fig. 6. a. Plan-position picture according to lower interferometer data. Direction of observation of the main interferometer is shown by the *arrow*. The horizontal beam width of this interferometer is shown by two straight segments surrounding the arrow. Change in the inclined shading illustrates the altitude difference at the eastern and western parts of the area. **b** Amplitude-slant range relief of the radar aurora. Regular character of the relief is sharply changed near the 800-km value for slant range. **c** Computer-calculated curves of the location of the elevation lobe maxima are given in altitude-slant range coordinates for the main (circles) and additional (triangles) interferometers. Black figures correspond to maxima, white to minima for each interferometer

the slant range axis of Fig. 6c. For each extremum there are at least three reasonable intervals of the altitude of scatter on the calculated curves; the intervals follow in a period of multiplicity of altitude, e.g. 90–95 km, about 110 km, and 125–130 km. In the 850–1,000 km slant range interval there are two altitude values with considerably less difference than the above period. Thus, this shows the existence of two truly different altitudes of scatter.

To resolve an ambiguity we use the data of the lower interferometer in the azimuth sector within the main lobe of the upper interferometer. In accordance with its halfwidth taken from Fig. 3, this sector is located from 333°–1°. First, it is at once clear that the scatter, at slant range values less than 800 km is caused by the radar auroral area with small azimuth size and situated westward from the main antenna gain direction. Second, the signal intensity extrema at the western part of the above sector are considerably shifted in slant range relative to the extrema near its eastern boundary. Thus there are marked differences of auroral echo altitudes at the sector boundaries. Therefore, we should plot the signal intensity extrema from Fig. 6a on the slant range axis of Fig. 6c separately. For the slant range interval from 550 to 800 km, provided that auroral echo occurs within a 90–130 km altitude interval, we obtain a unique altitude value of about 108 ± 3 km caused by the western radar auroral area. Corresponding to the location of the signal intensity extrema near the eastern boundary of the sector, we obtain an altitude value of about 117 ± 3 km. This value is confirmed by secondary extrema of the amplitude profile of the upper interferometer marked above in Fig. 6b. Moreover the slant range value at which a sharp change of the profile occurs agrees well with the value on the PPI at which the radar aurora azimuth size significantly increases. All these facts lead to the conclusion that the altitude lamination observed by the main interferometer at slant range values more than 800 km has been created by the presence of two auroral echo areas placed at different azimuths and at different altitudes. This phenomenon has been known since Booker's review (1960); we call it the east-western asymmetry of radar auroral altitudes. Its characteristics will be described in detail below. As seen in the example, when interferometers supplement each other, they provide a unique interpretation of the picture of altitudes of auroral echo. However, such a situation is not always possible. For example, in the same PPI frame at azimuth 5°–30° in a 700–1,200 km slant range interval, the picture of radar auroral areas is so irregular as to be practically uninterpretable.

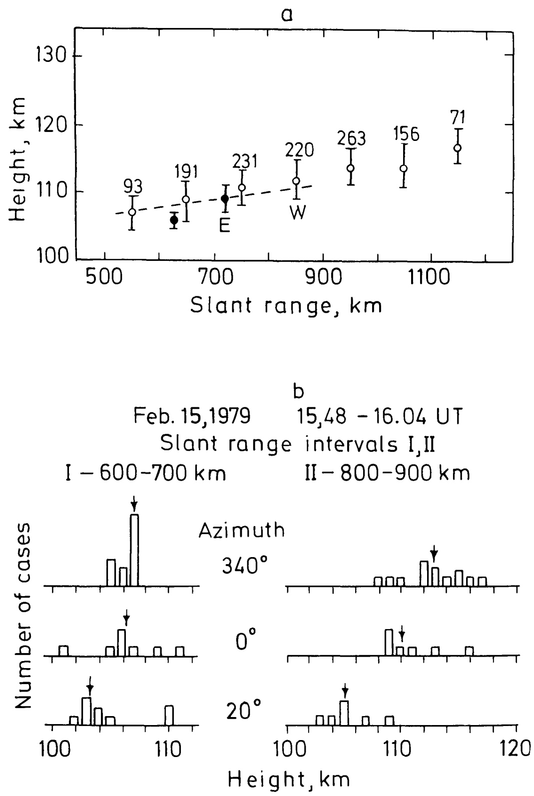

Fig. 7. a. Average radar auroral altitude dependence on slant range within the west- and eastward electrojets (*white and black circles*, respectively). The *dotted line* shows an average contribution of the standard tropospheric refraction; *vertical segments* show standard deviation. *Number* of measurements is given by digits separately for each slant range interval. **b** Radar aurora altitude histograms for varions azimuths illustrate the east-western asymmetry of auroral echo altitudes; medial values are marked by *arrows*

Another example is the observation results in which measurement multiplicity is eliminated in a similar way. Momenta, averaged for 6.5 s altitude slant range sections, are quite varied. They are not treated here in detail since they repeat qualitatively various types of such sections shown in Fig. 9 of Unwin's paper (1959). The average behavior of the altitude of scatter as a function of slant range agrees statistically with standard tropospheric refraction as shown in Fig. 7a. The radar auroral altitudes are averaged at azimuths within the radar view during a 4-hour observation period for the February 11th event and during a one-hour period (18–19 MLT) for the February 15th event. Standard deviation does not exceed 2 km for the latter event, despite the fact that less than half the number of measurements were made. This indicates a small variability of radar auroral altitudes within the eastward electrojet. The standard deviation for the February 11th event in the westward electrojet is approximately three times as large. The extreme altitude values for the event were 103 and 117 km. The average radar auroral altitude for the event was approximately 2 km higher than for the February 15th event.

East-Western Altitude Asymmetry

The quantitiative characteristics of azimuthal dependence of the radar auroral altitude will be described on the basis of a PPI data analysis. Sixteen PPI frames from February 15, 1979 and thirteen frames from February 11–12, 1979 were selected on the basis of the most homogeneous and azimuth-extended radar auroral areas. The intensity sections of the PPI frames within two slant range intervals of 600–700 and 800–900 km were compared for three different azimuths, e.g. 340°, 0°, and 20° for the February 15th event. The time difference between the observations of the extreme azimuths equaled only 8 s. The statistical approach applied in data processing allowed us to minimize errors associated with the uncertainty of the shape of the amplitude-slant range profile. These errors are inevitable in such indicators. The altitude distribution histograms obtained for the February 15, 1979 event are shown in Fig. 7b. The auroral echo altitude clearly decreases from the West to the East, especially within the second slant range interval. The differences in radar auroral altitude amount to 4–6 km for an azimuth difference of about 40° To adequately compare them with other geophysical data we expressed the azimuthal dependence of the radar auroral altitude as the altitude difference along a 100-km segment of the constant slant range circle. For the February 15, 1979 event an average value equaled 1.23 km. This azimuthal dependence of radar auroral altitude within the westward electrojet area was investigated by analysing the location of signal intensity minima on a scale of slant range marks at various azimuths. We selected pairs of azimuths for every PPI frame with a difference less than 20°–40° The eastern azimuth showed a lower radar auroral altitude for all the frames but one. The average value of incline, expressed in the convenient form mentioned above, was 1.31 km. Thus not only the incline direction but also the incline value of radar auroral altitudes are approximately equal for the east- and westward electrojets in these events. This is only an average value for the eastward incline, for at any given moment it can be totally different. A similar example was given in Fig. 6.

On the basis of the average value of the east-western asymmetry obtained for a 90-MHz radar frequency, the above-mentioned criterion for small azimuth size can be formulated. It follows from our results that the azimuth size should not be more than 10–15°, so that the difference of altitudes at the eastern and western boundaries of radar auroral area are not more than the accuracy of the altitude measurements, i.e., 1.5–3 km. For this reason we shall later assume that if the azimuthal size of the radar auroral area is larger than the above criterion value, an altitude lamination of scatter cannot be distinguished from the east-western asymmetry. Such an example was given in Fig. 6. If the criterion is satisfied and auroral echo from two different altitudes is registered, then either two radar auroral layers exist at once (one above the other at the same azimuth) or the altitude of scatter jumps subject to azimuth of observation.

Brief Information About Radar Aurora Thickness

The thickness of radar aurora layers was significantly different for each of the two selected substorms. The thickness measurements were complicated, especially for the westward electrojet event because of the sharp spatial structure of auroral echo along the slant range and considerable time dynamics. For verifiable results it was necessary to increase the time of averaging to several minutes. A detailed description of thickness behavior is outside the scope of this paper. Here we give only the average values. Preliminary estimations showed the average thicknesses to be about 15 and less than 2.5 km for the events of the east- and westward electrojet, respectively.

Local Double-Layer Altitude Structure

This type of structure was observed during the 11–12 February event consisting of several auroral substorms. The temporal

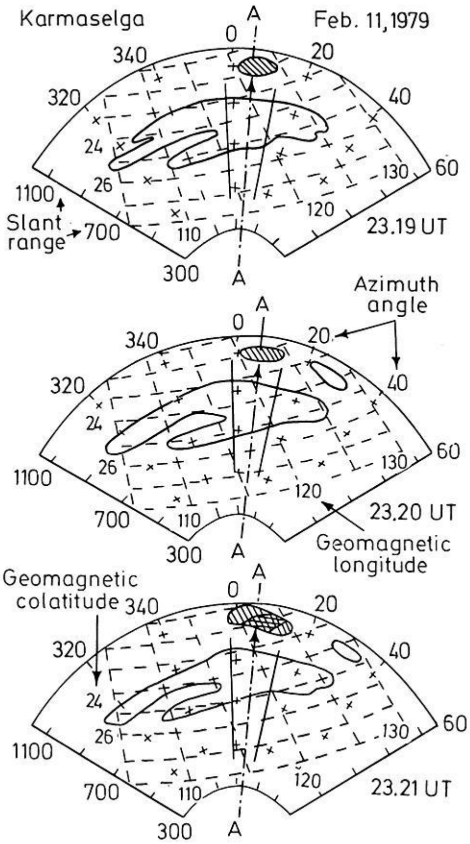

Fig. 8. Three consecutive PPI frames of the lower interferometer are given at the observation moment of double-layer altitude radar aurora by the upper interferometer. The local area of such scatter is shown by shading; its most intensive inner part, by double shading. Direction of observation of the upper interferometer is marked as the AA section and shown by *arrows*

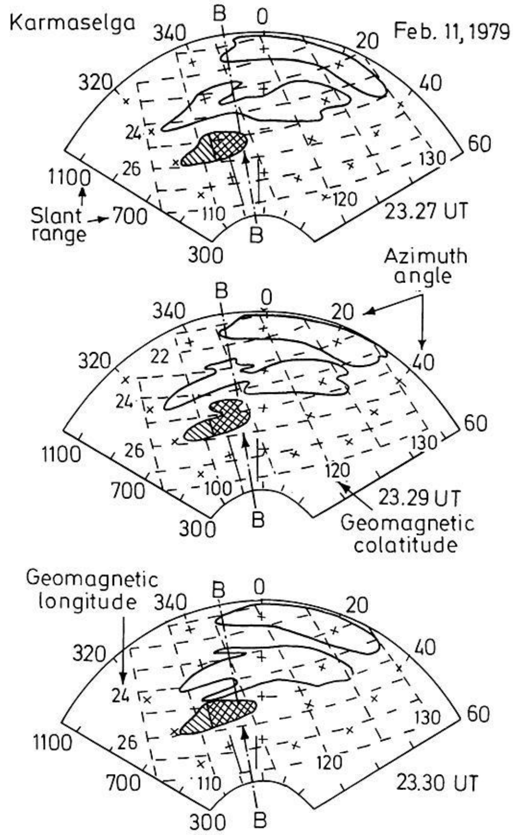

Fig. 9. PPI frames of the lower interferometer for the second fragment of the altitude lamination. The local area of the lamination is shown by shading; the part restricted by the horizontal beam of the upper interferometer, by double shading. Direction of observation of the upper interferometer is denoted as BB-section and marked by *arrows*

structure is clearly seen from the auroral magnetometer data given in Fig. 5. During this night the intensity of auroral echo signal was maximal for the whole period of our observations. As Fig. 4b shows, the auroral current intensity was also maximal for that night according to magnetometer data in Loparskaya. The radar aurora was observed for almost 5 h; at times it occupied the total radar coverage.

We will consider in detail two observation moments at about 23.20 and 23.30 UT on 11 February, 1979, which correspond to about 02.20 and 02.30 MLT. At these moments a splitting of the elevation lobe maxima was observed on the amplitude indicator as well as a shift of the neighboring minima along the slant range marks. It was unusual that such a picture was observed within a radar auroral area with a small azimuth size. Copies of PPI frames for these times are given in Figs. 8 and 9. For the first area of radar auroral lamination shown in Fig. 8, the azimuth size is less than 10°. At the end of this fragment it increases to about 20°. However, in its center is a more intensive part of the radar auroral area with a small azimuth size. The second area of radar auroral lamination shown in Fig. 9 has a full azimuth size of about 30°, but it was observed from one side of the main antenna gain direction. The latter passed near the eastern edge of the area being observed (arrow BB in the figure). Moreover the area has a homogeneous structure of scatter intensity like the DB-type radar aurora described by Tsunoda et al. (1974). That is why the main scatter intensity is determined by only the part of the area with a considerably smaller azimuth size. Restricted by the main horizontal lobe of the antenna of the upper interferometer, this part effectively has a size that corresponds to the width of the antenna directional pattern shown in Fig. 3c; along the 3 dB level, about 10°–15° at the beginning and end of the fragment; along the 10 dB level, about 15°–20°. Thus the criterion of small azimuth size formulated above is satisfied for both radar auroral areas. This means that they can serve as examples of a real double-layer altitude structure. Figures 10 and 11 give the amplitude slant range profile of a radar auroral signal for the two described areas. The quasi-periodic character of the profile reflects the multilobe narrow beam character of the antenna elevation directional pattern of the main interferometer. As is evident there are up to 3–4 different radar auroral altitude values. However, there are not more than two radar auroral layers with different altitudes in one and the same slant range interval (600–800 km in Fig. 11 and 900–1,100 km in Fig. 10). The double maximum in the 555th frame at a slant range of about 770 km is a typical example of a false double-layer altitude structure due to the sharp slant range inhomogeneity of the auroral echo signal. In contrast to the frames 565–575 there is no shift of signal amplitude maxima equal to that of its minima. In the frames 635–656 below the envelope curve, the course of scatter intensity is shown for each altitude value of radar auroral signals: by small crosses for 101–102 km, by points for 104–106 km, by dashed lines for 109–112 km. The analysis of model scatter was computed.

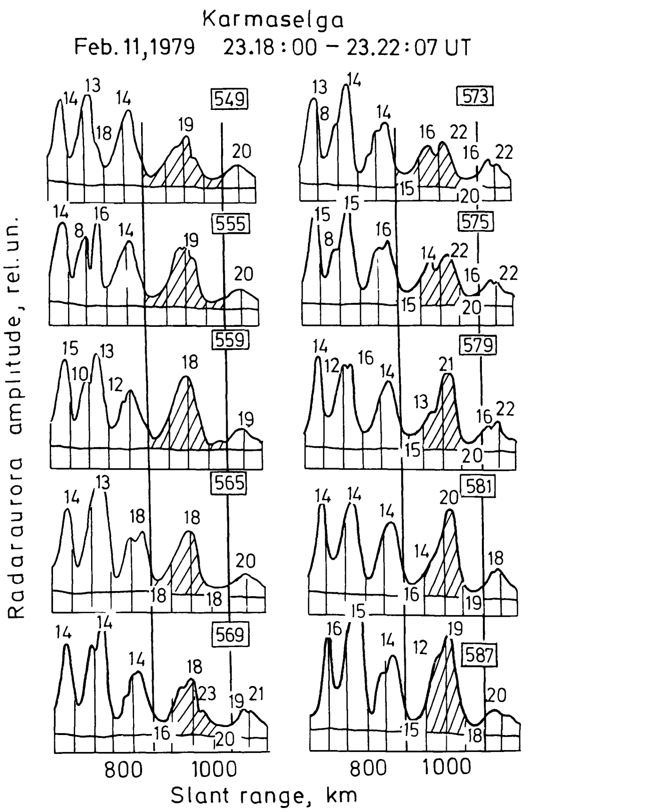

Fig. 10. Sequence of envelopes of radar auroral amplitude during the first fragment of lamination (AA-section of PPI frame is given in Fig. 8). Slant range intervals of the double-layer altitude radar aurora are marked by shading between *vertical lines*. The difference between altitude value and 100 km altitude is given near the corresponding extrema. Frame numbers are given in *rectangles*

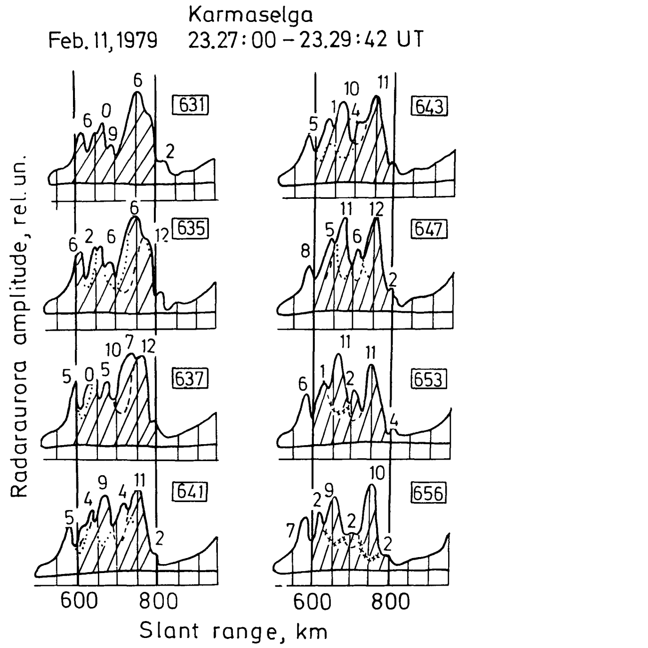

Fig. 11. Set of envelopes of radar auroral amplitude for the second fragment (BB-section of PPI frame is given in Fig. 9). Slant range intervals of the altitude lamination are shown by shading. The difference between altitude value and 100-km altitude is given near the corresponding extrema. Frame numbers are shown in *rectangles*

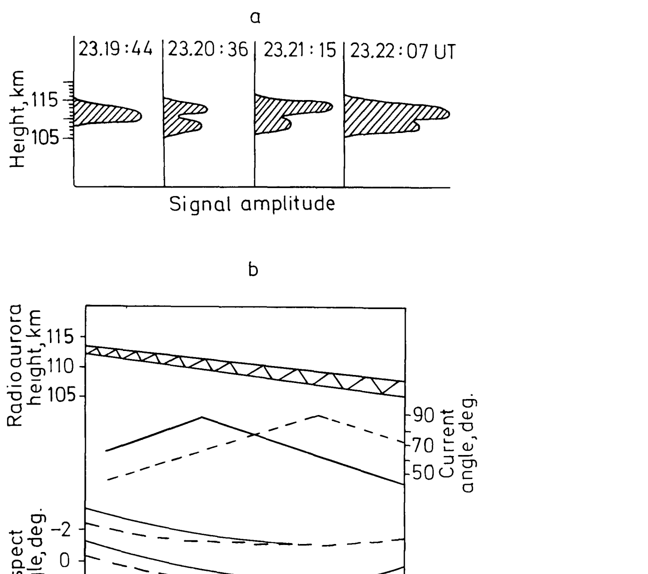

Fig. 12. a. The schematic representation of the doubler-layer altitude structure of the radar aurora and its time dynamics. The altitude values are given with the calculation of the standard tropospheric refraction. **b** Radar auroral altitude, aspect- and current-angle dependencies on azimuth of observation for the DAR radar (*solid lines*) and Homer radar (*dotted lines*). Aspect-angle dependence is shown for 90- and 120 km altitudes. Azimuth scale zero corresponds to local magnetic meridian for each radar

The Spatial-Temporal Characteristics of Lamination

The time variations of signal intensity of scatter occur independently in each of both layers. Increases of signal intensity from one of the layers may be accompanied by decreases in the other (Fig. 10, frames 579–581 in a 1,000 km slant range; Fig. 11, frames 653–656 in a 700–750 km slant range). An abrupt disappearance of radar aurora has been observed at 105 km altitude accompanied by small intensity variations (10–15%) at 110 km. A comparison of frames 647 and 653 clearly shows this. Sometimes there are increases of signal intensity simultaneously in both layers (frames 581–587 at a slant range of about 1,000 km, or in frames 643–647 at a 700–750 km slant range).

The time scale of dynamics of the double-layer altitude structure was determined as the duration of transitional processes such as: (a) the formation of the double-layer structure from a single layer; (b) the sudden decrease of scatter intensity from one altitude value and formation of a new layer of scatter at another. Two layers of scatter were formed at 116- and 121-km altitudes from a 118-km altitude layer in about 52 s. Both layers had almost equal scatter intensity, as seen in frames 565–573. About 50 s later the auroral echo intensity increased in the upper layer twofold (frames 573–581). Then after 40 s the intensities became approximately equal again. In the second fragment (frames 647–653) a sudden change in the radar auroral altitude from 105 to 101 km occurred in about 40 s. The time dynamics of the two altitude layer radar aurora for one of the fragments is given in Fig. 12a.

The double-layer altitude structure is localized only in the small part of the total area occupied by the radar aurora. The local character of the structure is illustrated by two examples in Figs. 8 and 9. The spatial scale of lamination along the meridian made up 100–200 km (frames 573–575 and 641, 653, 656, respectively). In the longitudinal direction the scale is restricted by the selection method itself (the criterion of small azimuth size). Thus we may only conclude that the longitudinal size is not less than 150–300 km. The corrected geomagnetic latitudes of observed lamination were 65° and 68°

The altitude scale of the double-layer altitude structure, determined as the altitude difference of radar auroral layers, changed from 5–6 km (frames 641 and 635) to 9–10 km (frame 653). These obtained values are known, in agreement with the DAR method, with accuracy only up to the period of altitude multiplicity. The maximum difference of the radar auroral layer altitudes was the same for both fragments, about 30 km with due regard for the dependence of the period value on the slant range (Fig. 3). With such great difference the upper layer of scatter should be observed at altitudes of 131–148 km. However, such an altitude interval is extremely unlikely at least in the light of our present knowledge.

The local double-layer altitude structure is quite a rare phenomenon as can be concluded from our first observations (it was observed for a few minutes during a total observation time of about a few dozen hours). It should be noted that the phenomenon coincided with the maximum of H-component variations on the Loparskaya magnetometer for the whole period, as seen in the chart in Fig. 4. The maximum variation value was 430 nT at 02.30 MLT on 12 February 1979. According to the magnetometer data from Apatity given in Fig. 5 for the event, this time is also near the maximum of the negative bay with intensity about 400 nT Unfortunately due to unfavorable weather conditions there were no aurora data at Loparskaya and Apatity observatories for the two events. Balloon measurement data are also lacking for the Apatity station. Therefore, we had only riometer data at our disposal for the analysis of auroral particle fluxes together with the double-layer altitude observations. The corresponding record of the Loparskaya riometer is given in Fig. 5. Thus, according to the available data the double-layer altitude radar aurora does occur within the area of the electron fluxes of the westward electrojet.

Discussion

Change in the radar auroral altitude as dependent on azimuth of observation or, in other words, east-western asymmetry of auroral echo altitudes, was described by Booker (1960) and also Harris and Kavadas (1973), Wang and Tsunoda (1975), and Tsunoda (1976). All their measurements were performed at radar frequencies from 398 to 1210 MHz. At lower frequencies, in particular at 90 MHz, the asymmetry was described qualitatively only by Pyatsi and Siekkinen (1978). According to our measurements, the value of asymmetry at this radar frequency is in good agreement with that obtained in the experiments at higher frequencies up to 1,210 MHz. This signifies that the value of asymmetry is approximately constant while the auroral irregularity size changes more by an order, of 12 cm to 1.65 m. However, the asymmetry is already absent for irregularities of 3.25 m as was reported by Pyatsi and Siekkinen (1978). The fact that Unwin's paper (1959) summarizing the program of altitude measurements for irregularities of 2.7 m does not report anything about east-western altitude asymmetry, proves, in our opinion, that it is negligibly small for these sizes of irregularity. Thus the asymmetry exists and has approximately constant value at radar frequencies higher than about 90 MHz and sharply decreases at about 50 MHz.

As described here, the average values of the altitude asymmetry are approximately the same within the east- and westward electrojets. This fact can be confirmed at higher radar frequencies by comparing Tsunoda's measurements (1976) at 398 MHz within the eastward electrojet and that of Harris and Kavadas (1973) at 448 MHz within the westward electrojet. The latter did not analyze the altitude difference at the eastern and western azimuths in detail. We have made this analysis using the data of altitude distribution given in Fig. 4 of their paper. In this case the values of the altitude slopes were close to the average value obtained by Tsunoda (1976). However, one half of the available six pairs of azimuths showed the eastward slope and the other half, the westward slope. This indicates that altitude asymmetry features are rather complex within the westward electrojet relative to the eastward one in spite of the equality of the averaged asymmetry values. This result is confirmed by Timofeev et al. (1980) who studied by DAR radar altitude asymmetry features, averaged for more than 3 h of measurements within the westward electrojet region. It was shown that within two 100-km slant range intervals distinct eastward altitude decreases took place with an average value of about 1.0. Within five other such intervals there was no tendency to altitude variations, i.e. west- and eastward slopes were observed with practically equal frequency. An average westward decrease was not observed at any slant range interval.

Azimuthal dependence or east-western asymmetry of the auroral echo altitudes cannot be explained by maintaining the constancy of aspect angle subject to the azimuth of observation. On the contrary, the real three-dimensional off-perpendicular contour is higher in the East. The asymmetry also cannot be accounted for by current vector rotation with altitude change. The rotation is supposed to be produced by the altitude variation of ratio of ionospheric conductivities. In this case if the radar chooses the altitude with a minimum or constant current angle value at each azimuth, the altitude is higher in the East again independently of the direction of electrojets. Wang and Tsunoda (1975) came to the same conclusion. It could be assumed that the altitude asymmetry of scatter reflects the difference in small and large current angle mechanisms of irregularity generation. This is similar to using the mechanism suggested by Farley (1963) under equatorial electrojet conditions to explain echos along the current direction, on the one hand, and using the mechanism suggested by Sudan et al. (1973) for the perpendicular direction on the other. Pyatsy and Siekkinen (1978) assumed the existence of such a difference in mechanisms for radar aurora since they formulated the experimental results in terms of a current angle. However, Timofeev (1980) showed that the asymmetry is not determined directly by the current angle, at least during its change from 40° to 90° A detailed comparison of observation conditions was made for the Homer radar (Alaska) and DAR radar at Kamaselga (Karelia, USSR) to prove this fact. These radar locations were chosen because they have the same corrected geomagnetic latitudes. Besides, the radars have very similar aspect-angle and an opposite current angle dependence on azimuth of observations. The angle between a radar ray and the geomagnetic latitude 65° for both radars was taken as the current angle. Results of the comparison are illustrated in Fig. 12b. The average asymmetry of altitudes is seen to be practically equal for both radars in spite of the contrary behavior of the current angle.

To explain the origin of the east-western asymmetry of radar auroral altitudes, Wang and Tsunoda (1975) applied the theoretical results of Kaw (1972), which he inferred for the equatorial electrojet. Kaw pointed out that the two-stream instability is a convective instability. In accordance with their concept, the eastward altitude decrease is observed within the eastward electrojet, and the maximum value of the asymmetry reasonably agrees with the half-thickness of the auroral electrojets. However, as can be concluded from the data of Harris and Kavadas (1973) and also of Timofeev et al. (1980), there is no reversal of the altitude decrease direction during the change of the electrojet flow direction to its opposite. This fact demonstrates the inadequacy of only explaining the east-western asymmetry of radar auroral altitudes on the basis of convection of two-stream irregularities. Later on we shall see that the situation will become clearer if we take into account not only the factors related to the radar aurora itself but also those reflecting the change of auroral flux parameters in the longitudinal direction. Recently data have shown that such change takes place not only statistically but also for individual auroral forms. Ivanov and Starkov (1977) pointed out the existence of an eastward altitude decrease for both the maximum luminosity and the lower edge of the quiet auroral arcs. The authors used simultaneous data from two pairs of all-sky cameras covering a considerable range of longitudes and located in the north of Siberia. For the same quiet auroral arcs, the zenith angle curves from the azimuth were constructed for each camera. Then by the approximation method, the altitude for each point on one of the curves was chosen so that this point coincided (within the experimental error) with the curve derived from the other station data. Having analyzed the behavior of the altitudes along 14 quiet auroral arcs in this way, the authors obtained an average incline value of about 3° This eastward incline remained at a distance of 400–600 km along the arc and then the altitude increased abruptly again. Another example of the existence of the eastward altitude incline for a sporadic ionization layer in the vicinity of a quiet evening auroral arc was shown by Timofeev et al. (1980). They analyzed the available simultaneous data for the 16 March 1978 event at Kiruna, Sodankylä, and Loparskaya ionosondes located approximately on the same corrected geomagnetic latitudes. The altitude difference between the Es_r-layer maximum from Kiruna to Loparskaya was 15 km.

In our opinion the data of the radar auroral altitude asymmetry indicates the presence of longitudinal change in electron flux parameters that are responsible for the formation of current layers containing auroral irregularities as in both the above examples. The similar features of these altitude variations are supported by a close correlation of radar aurora and sporadic ionization layer altitudes described in the same paper. Altitude behavior was studied for about 4 h on the basis of data from DAR radar and the Loparskaya ionosonde which referred to the same ionospheric region over the Loparskaya observatory. The correlation coefficient was about 0.75 for the "r" type of E_s layers. All these facts have led us to conclude that current streams of increased intensity with small eastward altitude inclines occur within the range of the electrojet altitudes. If this hypothesis is true, then the effects of the current incline and the convective drift of unstable plasma waves will coincide within the eastward electrojet and will intensify each other. In contrast, both factors will have an opposite direction within the westward electrojet. Therefore, the eastward altitude incline of the radar auroral layers will be constantly within the eastward electrojet. On the contrary, both eastward and westward altitude variations will often occur in the region of the westward electrojet, as observed in the above experiments. From this point of view, it is easy to understand the disappearance of radar auroral altitude asymmetry described above, which occurs at low radar frequencies. Indeed, the low frequency auroral scatter does not reflect the altitude variation of current layers because, as is well known, it is much less directly connected with the current drift velocity but is determined to a greater degree by ionization gradients. Apparently, the average altitude variation of the current structures exists only within the limits of the usual width of radar coverage along the auroral oval. In the experiments described this width was not more than 600–700 km.

The double-layer altitude structure of radar aurora was observed within diffuse layers of auroral echo similar to the DB-type described by Tsunoda et al. (1974). Unlike the diffuse radar aurora in general, this double-layer type has a local character. Moreover this structure is closely connected with the maximum variations of riometer absorption and auroral current intensity. A similar altitude structure of electron ionization profiles was observed in Chatanika with incoherent scatter radar by Baron (1974) approximately at the same geomagnetic latitudes. Its lifetime was nearly the same as that of radar aurora (about 20 s). Stenback-Nielsen and Hallinan (1979) observed the lamination of the altitude profiles of auroral luminosity by stereo-TV technique. The thickness of luminosity layers was about 1.5 km and the lifetime equaled several seconds.

According to Rees's (1963) calculations of ionization profiles formed by incident auroral electrons, such a sharp altitude structure cannot result from the double-peak energy spectrum of fluxes. Shepherd and Fälthammer (1980) have shown that a similar structure is also not a result of acceleration of incident electrons in a field-aligned electric field. Stenback-Nielsen and Hallinan (1979) came to the conclusion that a collective interaction of electron fluxes with E-region ionospheric plasma causes the lamination. Timofeev and Miroshnikov (1979) independently arrived at the same conclusion by interpreting the first results of measurements with the DAR radar. Their interpretation was based on the results of the theoretical paper by Izhovkina and Mishin (1978). These authors showed that a rather sharp double-layer altitude structure of ionization could be caused by a fairly dense and monoenergetic electron beam. According to their model, a supplementary maximum of energy dissipation, due to collective beam-plasma interaction processes, may exist in addition to that of the collisional one. The collective dissipation is mostly effective within a thin (about 3-km) layer, the upper boundary of which is determined by the collisions suppressing the collapse of plasma caverns. These caverns are created by a modulational instability of Langmuir oscillations caused by the beam. The layer's lower limit is determined by the suppression of beam instability resulting from the increase of the collision frequency. On the basis of this model Mishin and Timofeev (1980) estimated quantitatively the features of similar double-layer radar aurora, taking into account real parameters of auroral fluxes. On the other hand, if we try to understand the origin of such an auroral echo structure within the framework of the gradient-drift or two-stream machanisms, we must assume that extremely sharp altitude gradients of short duration exist in the E-region of the auroral ionosphere. Such an assumption seems quite artificial since the origin of the gradients is not clear.

This splitting of signal maxima on the amplitude range indicator, similar to that shown in Figs. 10 and 11, may be interpreted in another way. The picture may be formed as a result of a jump in the radar auroral altitude subject to the azimuth of observation. For this situation only a rather small azimuth scale of the jump (10°–15°) is necessary. As already mentioned, similar altitude jumps were discovered for quiet auroral arcs by Invanov and Starkov (1977).

Observations of diffuse radar auroral layers with 2-km thickness confirm the result of Unwin (1959) obtained for irregularities almost twice as large. None of the ionospheric parameters determining irregularity generation within the framework of the linear theory has such a small altitude scale of change. This shows once more that it is necessary to solve non-linear problems to understand the nature of radar auroral generation.

Conclusion

In summary, the results obtained by the DAR method successfully combine both high accuracy and uniqueness of measurements:

1. The auroral echo altitudes are much more variable within the westward than in the eastward electrojet region.

2. The average value of the east-western asymmetry of the radar auroral altitude is about the same at 90 MHz radar frequency as at higher frequencies (up to 1,210 MHz). Moreover the average value and direction of this altitude variation are the same for the east- and westward electrojets. Because of this we cannot explain the origin of the altitude asymmetry as only due to the convective character of the two-stream instability. Therefore, to explain the whole complex of experimental data it is necessary to assume the existence of an additional cause for this altitude variation. There is definite proof that a real eastward altitude decrease of current structures exists within the auroral electrojets with an average slope of about 1°.

3. A double-layer altitude structure has been discovered for the local areas of diffuse radar aurora within the westward electrojet. Its space-time parameters have been described. We conclude that such a structure is formed in the lower ionosphere due to a mechanism of the collective interaction of electron fluxes with surrounding plasma.

4. The thickness of radar auroral diffuse layers within the westward electrojet cannot be greater than 2.5 km.

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