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Observations of the upper frequency cutoffs of the auroral kilometric radiation

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Abstract. Intense auroral kilometric radiation (AKR) is being frequently observed with POLRAD from the Auroral Probe (Interball-2). Observations of the abrupt upper frequency cutoffs (UFCs) in the spectra of AKR are reported. The UFCs can be observed at a frequency range from 300 to 700 kHz, corresponding to AKR generation altitudes from approximately 4800 to 2100 km, and are distributed in magnetic local time (MLT) hours similarly to the AKR events, with a maximum at 1 h MLT. The observed frequency extent of the UFCs is ≤ 12 kHz, and is often determined by the instrumental resolution (4 kHz). It is suggested that the UFC may be associated with an abrupt switching on of the generation mechanism, when the electron density becomes sufficiently low inside a plasma depletion at an altitude where the ratio of f_{pe}/f_{ce} crosses some threshold value. The steepness of the UFCs can imply a non-linear process of generation. The estimated distance of the e-folding field aligned wave amplification is between 3 and 8 km. The UFCs are sometimes, though very seldom ($<10\%$), accompanied by narrow band (less than 4 kHz) “ridges” of radiation observed at the cutoff frequency. They are smoothly drifting in frequency for several minutes. The power density of radiation in the “ridge” can be up to 2 orders of magnitude stronger than in the accompanying wide band emission of AKR. The “ridge” at UFC can imply either energy concentration at the source bottom, or focusing, if specific conditions for the escape of the radiation are assumed.

Key words. Magnetospheric physics (auroral phenomena; plasma waves and instabilities) · Radio science (magnetospheric physics)

1 Introduction

Interball-2, the second spacecraft of the Interball project, also called the Auroral Probe, is aimed at studying dissipation processes of the energy transferred to the auroral region along the open magnetic field lines from the magnetospheric tail. Some contribution to this dissipation is auroral kilometric radiation (AKR), a strongly variable radioemission occurring in the frequency range from about 30 kHz to 1 MHz, with a maximum intensity at around 300 kHz. Spectral observations of the AKR carried from Interball-2 with POLRAD instrument generally confirm previous observations, but add also some new information to spectral structures of the AKR. They will be described and discussed in this work.

The Interball-2 spacecraft was launched into an elliptical orbit with the apogee at 19140 km, and perigee at 780 km, inclined to the equator for 62.8° , with a nodical period of 5.9 h. It crosses the radiation belts eight times a day. For safety purposes POLRAD has been operating only outside the radiation belts, that is at $L > 4.5$. With this restriction, data acquisition on AKR is being continuously performed in sessions lasting up to 4 h every orbit, when the spacecraft moves in the auroral region or the polar cap, at altitudes above 9000 km, and covering invariant latitudes from 63° to 80° .

AKR, first reported by Benediktov *et al.* (1965), most likely originates in the nightside auroral magnetosphere, at invariant latitudes of about 70° (Gurnett, 1974), (Kurth *et al.*, 1975), several thousand kilometres above the Earth's surface. It is mostly observed in the right handed extraordinary mode. The Viking observations (de Feraudy *et al.*, 1987) have shown that the sources of the AKR are plasma cavities, sharp edged narrow structures, presumably field aligned with a very low plasma density. The lowest sources of the AKR were met by the low orbiting ISIS-1 satellite at 2000 km

(Benson and Calvert, 1979), while the highest reported ones were crossed by Swedish Viking at about 9000 km. This altitude can be deduced from the study of radiating and nonradiating plasma cavities made by Hilgers (1992). It has been established by Benson and Calvert (1979), James (1980), Calvert (1981), Benson (1985), and Bahnsen *et al.* (1989), that the AKR is generated at the local cyclotron frequency of electrons. Thus irregular and variable structures in the dynamic spectra of remote sources can be related to spatial structures of the source regions. Gurnett and Anderson (1981) interpreted the fine structures in the AKR spectra in terms of motions of the compact sources.

Observations in situ of several AKR source crossings from Viking have provided evidences that the AKR can be associated with precipitating electrons trapped in parallel electric fields of the plasma turbulence (Louarn *et al.*, 1990). Among a number of mechanisms of the AKR generation the most widely accepted one relies on the electron cyclotron maser instability (CMI), proposed by Wu and Lee, (1979). It can work efficiently in density depletions, where the local plasma frequency is much lower than the electron gyro-frequency.

In this study, we present some spectral structures observed with POLRAD, characteristic by their steep cutoffs at the upper frequency limit of the AKR spectra, that, to our knowledge, have not been previously reported. We shall call these kinds of structures upper frequency cutoffs (UFCs) (Fig. 1). Occasionally, UFCs are accompanied by narrow band “ridges” of emission, at the upper frequency cutoffs (Fig. 2), which consist in enhancements of the AKR intensity by 2 orders of magnitude.

POLRAD is a swept frequency radio-spectrometer, covering the frequency range from 4 kHz to 2 MHz with a frequency resolution of 4 kHz. Some AKR fine structures have also been observed with MEMO, another wave experiment on board of Interball-2, operating at a lower frequency range from 5 Hz to 240 kHz for short time intervals, but with much better time and frequency resolution. However, the UFCs have not been observed by MEMO, in agreement with POLRAD observations which show that they do not occur below 300 kHz.

Data from the POLRAD experiment related to the upper frequency cutoffs (UFCs) and “ridges” are described in Sect. 3. In discussion (Sect. 4) we suggest that the conditions for exciting the instability, from which the AKR originates, sharply depend on the plasma density. Above some threshold value the generation no longer operates. The instrumentation is described in Sect. 2, and conclusions are made in Sect. 5.

2 Instrumentation

The wave complex on board Interball-2 consists of 4 independent experiments: POLRAD, the radio-spectro-polarimeter for the frequency range from 4 kHz to 2 MHz, MEMO the wave analyser aimed for the determination of wave characteristics and wave interac-

tions in the frequency range from 5 Hz to 240 kHz, NVK-ONCH, the wave analyser for the frequency range from 10 Hz to 22 kHz, and IESP, the wave analyser working from 0.1 to 30 Hz.

POLRAD can be used either as a radio-spectro-polarimeter, or as a radio-spectrograph. For our purpose only spectrographic data have been analysed. The use of POLRAD as a polarimeter will be presented in another paper. POLRAD as a radio-spectrograph can use 1 or 3 antennae. Their coordinate system is fixed to the spinning spacecraft (1 revolution in 2 min). One antenna is an 11 m monopole (tip-to-spacecraft centre) oriented along the spin axis in an anti-solar direction. The other antennae are 2 crossed dipoles, 22 m tip-to-tip, perpendicular to the spin axis. The size of the monopole, which is half as long as the other dipoles is compensated by the doubled voltage gain of its preamplifier. The antenna diameter is 25 mm.

In the spectrograph mode the power spectra of signals received from each antenna are measured in separate channels. The step increment of SFA is 4.096 kHz, while the half-power bandwidth is 2.7 kHz. The step filters were made with a special care to have narrow wings, so that the power leakage between successive frequency steps is about 4%. The instrumental frequency profiles of the monochromatic calibration signals measured every 4.096 kHz by the radio-spectrograph are inserted in Figs. 1c and 2c. POLRAD can be swept over several frequency ranges selected between 4 kHz up to 2 MHz. The frequency range most frequently used can be set from 4 to 491 kHz (120 steps), or from 4 to 983 kHz (240 steps). The sweep rates can be set to 25, 50, or 100 ms per step. The resulting sweep periods, that are most frequently used, are 6 or 12 s. The time constant of the output detector is 6 ms. It is thus much shorter than the duration of a single frequency step. The characteristics of the filters and output detectors make a single measurement at one frequency step practically independent from that in preceding one. This favours detection of spectral structures, whose bandwidths are comparable with the frequency interval of a single step.

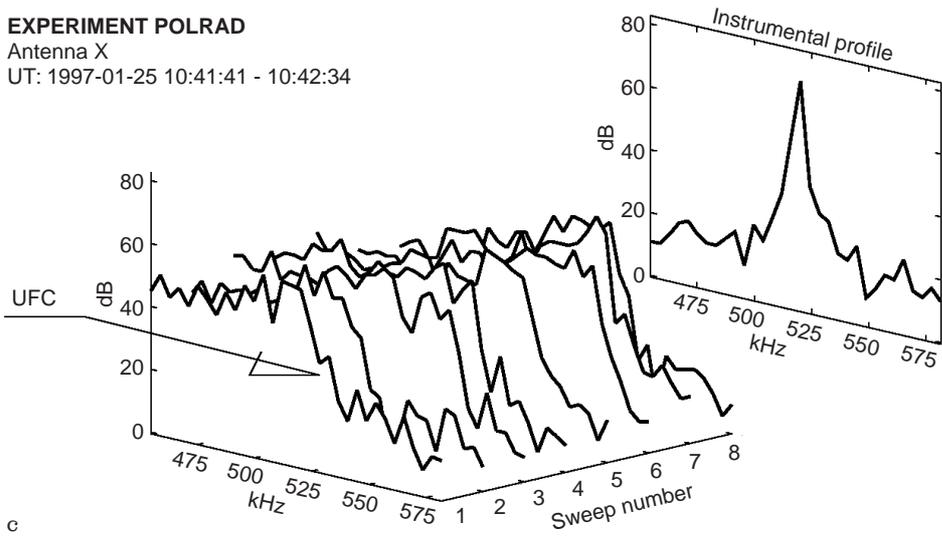
The sensitivity of the instrument is determined by the noise level of the antenna amplifiers. At several frequencies it is limited by onboard interferences. The latter are dominating and can be seen in the spectrograms as strong horizontal lines of almost constant amplitudes. Some of them occur at frequencies



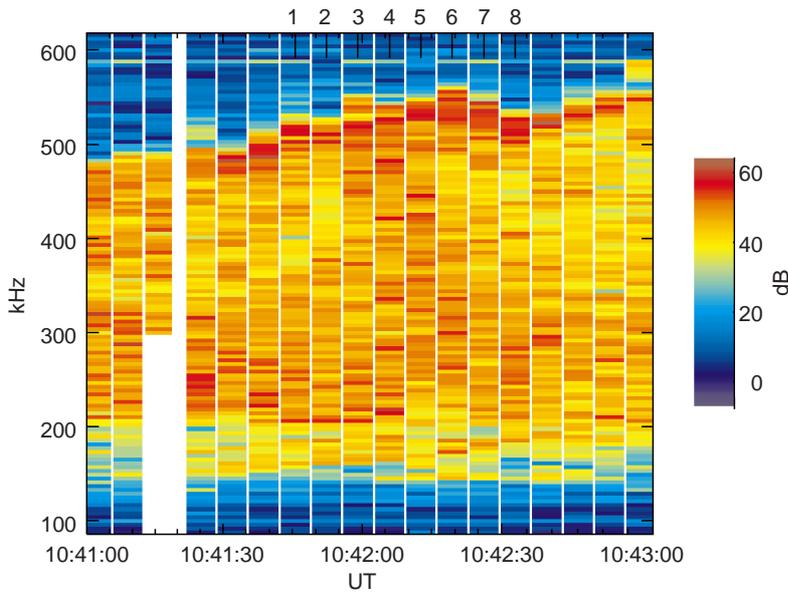
Fig. 1a-c. The dynamic spectrum of the AKR showing upper frequency cutoffs, obtained with POLRAD on the 25th of January, 1997. **a** A quick look 1 h spectrogram received with the antenna X. Upper frequency cutoffs (UFCs) are indicated by *bars* above the spectrogram. Power density estimated from the colour scale should be multiplied by 100 to compensate the 20 dB input attenuation of the receiver. **b** Zoom of the same spectrogram showing the detailed spectrum of one of the UFCs in time interval from 10.41 to 10.43 UT. **c** Eight selected frequency profiles for the SFA sweeps indicated by *numbers* in the middle panel. The profiles are built up from points separated by 4.096 kHz intervals (SFA frequency steps). For comparison the instrumental frequency profile of channel X is shown

EXPERIMENT POLRAD

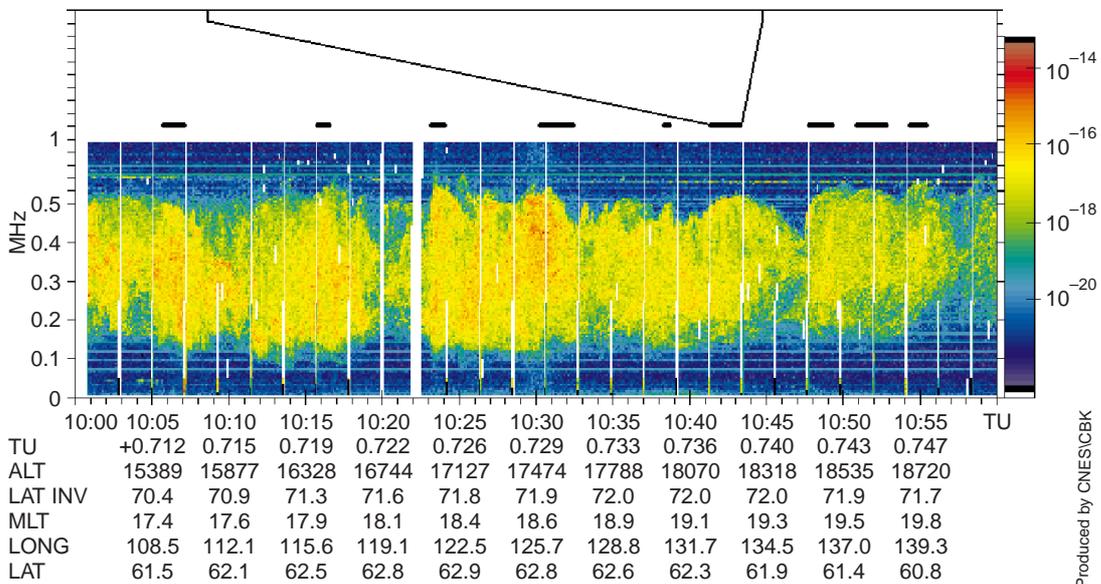
Antenna X
 UT: 1997-01-25 10:41:41 - 10:42:34



c



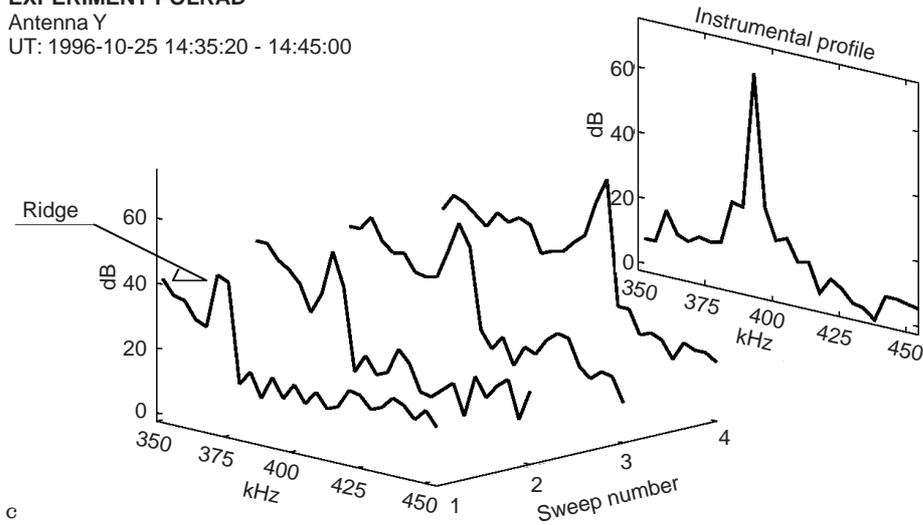
b



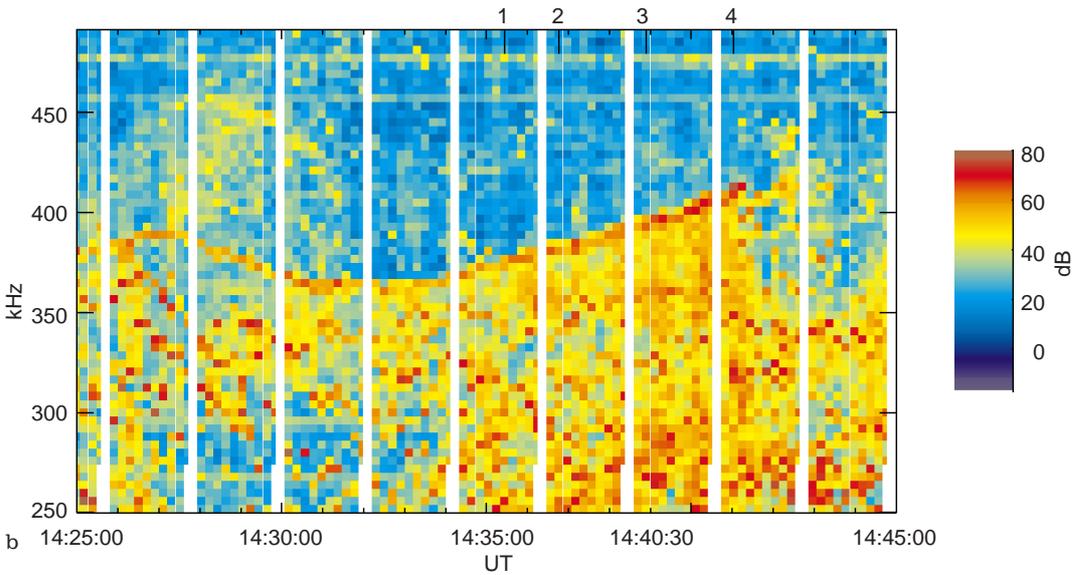
a

EXPERIMENT POLRAD

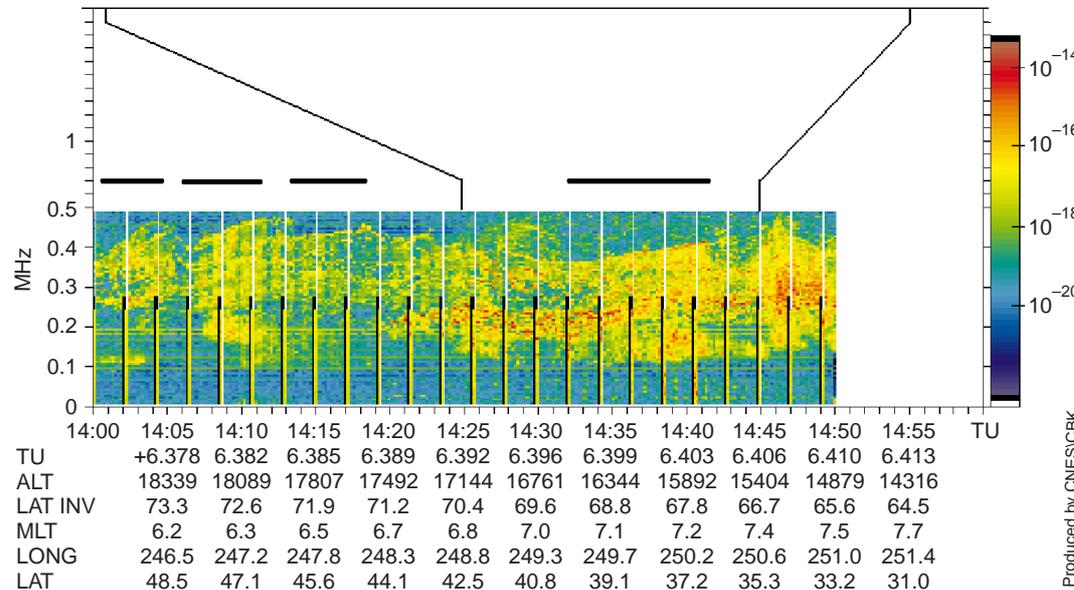
Antenna Y
 UT: 1996-10-25 14:35:20 - 14:45:00



c



b



a

	14:00	14:05	14:10	14:15	14:20	14:25	14:30	14:35	14:40	14:45	14:50	14:55
TU	+6.378	6.382	6.385	6.389	6.392	6.396	6.399	6.403	6.406	6.410	6.413	
ALT	18339	18089	17807	17492	17144	16761	16344	15892	15404	14879	14316	
LAT INV	73.3	72.6	71.9	71.2	70.4	69.6	68.8	67.8	66.7	65.6	64.5	
MLT	6.2	6.3	6.5	6.7	6.8	7.0	7.1	7.2	7.4	7.5	7.7	
LONG	246.5	247.2	247.8	248.3	248.8	249.3	249.7	250.2	250.6	251.0	251.4	
LAT	48.5	47.1	45.6	44.1	42.5	40.8	39.1	37.2	35.3	33.2	31.0	

Fig. 2a–c. The dynamic spectrum showing “ridges” at upper frequency cutoffs of AKR emission, obtained with POLRAD on the 25th of October 1996. **a** A quick look at 1 h spectrogram received with the antenna Y. The “ridges” at upper frequency cutoffs are indicated by *bars* above the spectrogram. Power density can be estimated from the colour scale (no input attenuation). **b** Zoom of the longest “ridge” seen from 14.25 to 14.41 UT. **c** Four selected frequency profiles for the SFA sweeps indicated by *numbers* in the middle panel. The profiles are built as in Fig. 1. For comparison the instrumental frequency profile for channel Y is shown

$n \times 24.57$ kHz. The sensitivity of the instrument is 2.5×10^{-20} W/(m² Hz), if the theoretical impedance of the short dipole in vacuum is assumed. To avoid signal saturation and generation of harmonics in the wide band antenna amplifiers, the programmable input attenuation can be applied. Frequently used is the attenuation of 20 dB, which efficiently reduces these instrumental effects. The output signal of the receiver is proportional to the logarithm of the input voltage.

The instrument has an additional active mode aimed at the determination of the frequencies of the plasma resonances, excited in the ambient plasma by a built-in relaxation sounder. Its operation interrupts the passive reception, which is seen in the spectrograms as periodic vertical gaps, every 2 min 8 s.

The mode of operation, sweep rate, antenna selection, frequency range, and input attenuation can be controlled from the ground. Detailed description of the equipment and POLRAD experiment can be found in Hanasz *et al.* (1995).

3 Observations

The AKR was very frequently observed with POLRAD during the first year of Interball-2 operation. Its dynamic spectra are usually smooth at upper frequencies. However, some of them demonstrated abrupt cutoffs at upper frequencies, which we call the upper frequency cutoffs (UFCs). We define the UFC as a flat spectral structure of AKR, whose intensity decreases abruptly at its upper frequency limit at least for 100 times in no more than 12 kHz (three steps of 4 kHz bandwidth). It may be noted that some UFCs are so steep that their frequency profiles are determined by the instrumental bandwidth of 4 kHz. The examples of UFCs are shown in Fig. 1a. It may be noticed that the AKR spectra are rather flat at frequencies below the UFC, indicating that the generation and propagation conditions do not change much for emissions at frequencies below the cutoff.

The UFCs are occasionally accompanied by narrow band enhancements of emission, which we call the “ridges” of emission, observed at the upper cutoffs (Fig. 2). Their observed bandwidths are comparable with instrumental ones. In the following subsections we shall discuss these structures separately.

3.1 Upper frequency cutoffs

The bottom panel (Fig. 1a) shows a quick-look spectrogram received on January 25, 1997 with the antenna X, parallel to the spin axis of the spacecraft.

The UFCs are seen in a number of time intervals, lasting from 30 s to 4 min indicated by horizontal bars above the spectrogram.

The frequencies of single UFC structures vary over tens of kHz. With different slopes, positive, zero and negative, the UFCs dynamic spectra are reminiscent sometimes of bell-shaped structures. In this example they occur between 430 and 650 kHz. At the same time the local gyro-frequencies of electrons, determined by the on-board magnetometer vary from 25 to 40 kHz. The UFCs must be features of the remote AKR, if generation at the gyro-frequency of electrons is accepted.

It can be concluded from review of the data received during one year of spacecraft operation, that the occurrence of the UFCs is limited to the frequency range from 300 to 700 kHz and durations from seconds to tens of minutes.

An enlarged view of the UFCs structure is presented in Fig. 1b, in which every sweep of the SFA can be seen as a vertical strip. The period of sweep repetition is 6 s, the step duration is 25 ms. In this panel every single 4 kHz step can be easily identified in order to see variations in the detailed structure of UFC. Some eight sweeps, indicated by vertical ticks have been selected to draw their frequency profiles (Fig. 1c). The mean slope (mean spectral index) of UFC is large, 6 dB/kHz, which is not much less than the instrumental one, 9 dB/kHz.

We have found 515 cases of UFCs in spectrograms recorded by POLRAD in the first year of Interball-2 operation, from September 4, 1996 to October 8, 1997. The selection comprises all the cases equal to or longer than 1 min. Most of them lasted for 1 to 5 min, but there were some of up to 70 min. Figure 3a shows distribution of spacecraft positions at times of UFC observations. One can see that most frequently the UFCs were observed when the spacecraft was around 1 h of magnetic local time (MLT). The number of cases decreases smoothly to 0 at noon MLT from evening and morning sides. The preponderance of cases after midnight (0–3 h MLT) is clearly pronounced. Frequent occurrence of UFCs at the day side can be explained either by the existence of sources associated with UFCs at the dayside polar magnetosphere, or by transpolar propagation of radiation, facilitated by relatively wide “horizon” of the AKR visibility from the spacecraft observing mostly at apogee part of its orbit. From Fig. 3b it is clear that the maximum occurrence is observed at satellite positions corresponding to the 71° invariant latitude. The distribution comprises the zone of 24 h of MLT and invariant latitudes from 64° to 80° covered by orbits of Interball-2 in 1 y. It can be seen that number of cases versus invariant latitude follows the distribution of integrated times for 1 y of POLRAD operation. The

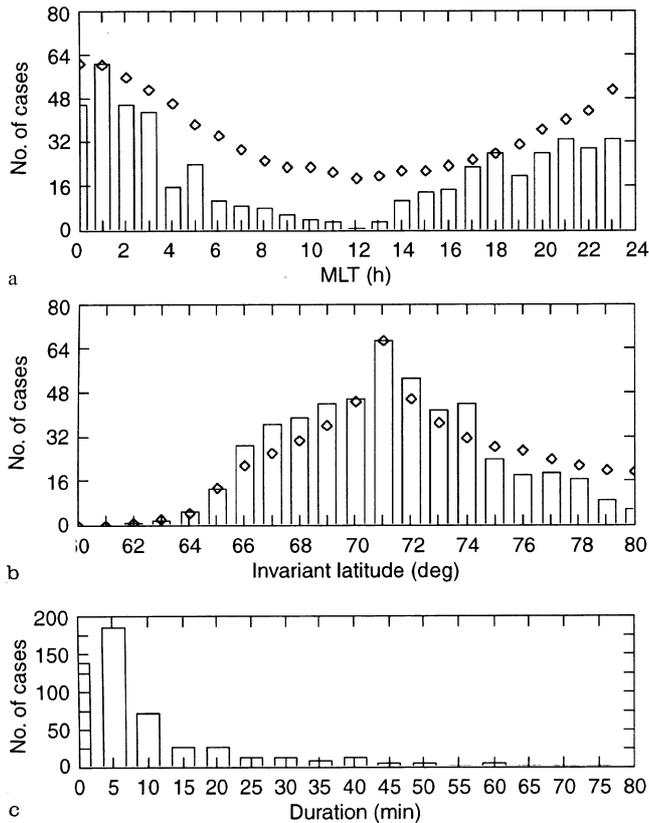


Fig. 3a–c. Statistics of 515 cases of UFCs recorded by POLRAD from September 4, 1996 to October 8, 1997. The selected cases are not shorter than 1 minute. **a** Distribution of spacecraft positions in MLT hours at times of UFC observations. **b** Distribution of spacecraft positions in invariant latitude at times of UFC observations. **c** Frequency of occurrence of UFC durations. On **a** and **b** values proportional to the integrated times of one year POLRAD operation are superposed (symbols)

distribution over MLT shows a deficiency at noon hours, which could be expected.

3.2 “Ridges” at upper frequency cutoffs

Filamentary fine structures of 4 kHz bandwidth were observed frequently with POLRAD. In most cases they can be classified as narrow drifting bands already observed from other spacecraft (ISEE, JIKIKEN, DE-1, Galileo) and described by Gurnett and Anderson (1981), Calvert (1982), Morioka *et al.* (1981) and Menietti *et al.* (1996). However some structures, like those shown in Fig. 2a, indicated by horizontal bars above the spectrogram, are different. They are single narrow drifting bands located at the upper cutoff frequency of the AKR, accompanied by a weaker wide emission at lower frequencies. We call them here the “ridges” at upper cutoffs.

The enlargement of the most pronounced “ridge” at UFC is shown in Fig. 2b. It can be noticed by comparison with the instrumental frequency profile, that its observed bandwidth is about 4 kHz (1 step of SFA). It starts at about 14.25 UT and continues to

14.41 UT, lasting for 16 min. At the beginning this is a strong drifting downward narrow band structure, seen over the weak AKR broad band emission at higher and lower frequencies. In this phase it looks like other drifting fine structures known from previous experiments. At 14.29.10 UT the emission at frequencies below it begins to be stronger than above. At 14.31.15 UT the emission above it disappears into the receiver level. Till the end at 14.41.00 UT the “ridge” is seen at the UFC. The structure stays for 4 min at a constant frequency and at about 14.33 UT it begins to drift upward. Its intensity increases slowly together with the wide band emission below it.

In Fig. 3c we draw the line spectra of several sweeps to show examples of the frequency profiles taken at different times of the structure development. It can be noticed that in this e.g. (1) the “ridge” is stronger than the accompanying AKR background by almost 20 dB, with its intensity increasing from 20 to 40 dB above the instrument noise level, and (2) the slope of the frequency profile is about 5 dB/(kHz).

There are three other “ridges” indicated by bars in this spectrogram. They are shorter and not as strong as the one described.

The series of “ridges” observed on October 25, 1996 seems to be exceptional. It must be admitted from visual inspection of quick look spectrograms, that the number of “ridges” at UFC met till now in POLRAD data is about 30, much less than the number of UFCs. Their duration can be even as short as 1 min.

3.3 Summary of observational results

Now we can summarise general observational features of the upper frequency cutoff (UFC) structures:

1. The UFCs are frequently observed spectral features of the AKR, with a frequency extent of 4 to 12 kHz.
2. The UFCs are structures drifting in frequency, with a variety of patterns in the dynamic spectra, sometimes of bell-shape.
3. The UFCs are features of remote AKR. Their frequencies can vary from 300 to 700 kHz.
4. The “ridges” at UFCs are observed occasionally. They have an extent of about 4 kHz, and power densities up to 2 orders of magnitude larger than that of the simultaneous low frequency wide band emission of the AKR. The “ridges” are structures slowly drifting in frequency, which can last up to 15 min.

4 Discussion

The spectrum of AKR can be considered as a superposition of contributions radiated by a chain of elementary sources extended along the auroral magnetic field lines and emitting close to the local gyro-frequencies of electrons. The cutoff at a given frequency can be related to the bottom of the source, located at an altitude determined by its local gyro-frequency of electrons. The

frequency range of the observed UFCs, from 300 to 700 kHz, corresponds to altitudes of source bottoms from approximately 4800 to 2100 km for invariant latitude of 70° .

For the UFC width of 4 kHz (1 SFA step) the vertical distance between strongly radiating and non-radiating levels of a source should be no more than about 20 km at frequency 530 kHz, corresponding to the source bottom at an altitude of around 2900 km (Fig. 1). From the measured spectral indices of the frequency profiles plotted in Fig. 4 the e-folding field aligned distances of amplification have been estimated to be between 3 and 8 km.

We learn from the observations reported here that the generation process must be very sensitive to threshold conditions within the plasma depletion. It is known that the field-aligned gradient of electron density is critical for the generation mechanism. At some low altitude, when the ratio of f_{pe}/f_{ce} becomes sufficiently small, the mechanism switches on at the corresponding gyro-frequency. According to the CMI theory (Wu and Lee, 1979) the most intense R-X mode can be produced provided the plasma frequency is much lower than the gyro-frequency of electrons inside the source. The threshold value of f_{pe}/f_{ce} was theoretically calculated by Melrose *et al.* (1984) to be ≤ 0.3 for 4 keV electrons, and was experimentally determined by Hilgers (1992) to be even ≤ 0.14 . It can be expected that such values can be met at altitudes of source bottoms determined from frequencies of UFCs. Steepness of the UFC suggests that the growth rate of emission increases rapidly when the ratio of f_{pe}/f_{ce} inside the plasma depletion decreases below some threshold value. The rapid response of the generation mechanism to continuously varying electron density points towards the non-linear character of the process.

The “ridges” at first sight are similar to the AKR fine structures reported in a number of papers, see for example Gurnett and Anderson (1981), Calvert (1982), Morioka *et al.* (1981), Baumbach and Calvert (1987),

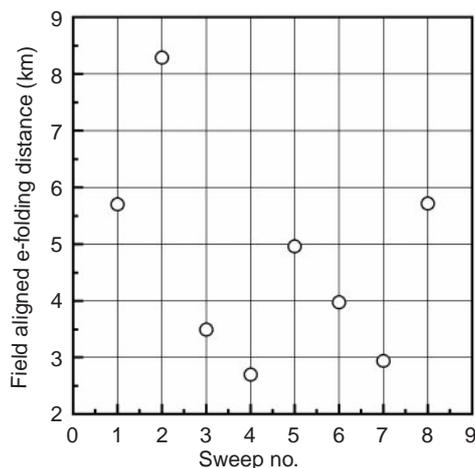


Fig. 4. The e-folding field aligned distances (expressed in kilometres) of the emission growth at the upper frequency cutoff, estimated for selected sweeps (1 to 8) of the case observed on January 25, 1997

Menietti *et al.* (1996). Though the idea “fine structure” includes different time and frequency scales (Menietti *et al.*, 1996) we distinguish the “ridges” as a separate class of fine structures due to their position exactly at UFCs.

There are, in our opinion, two possible approaches to explanation of these structures: (1) in terms of a generation mechanism, and (2) in terms of propagation effects. In the first approach the “ridge” emission could be interpreted in the frame of the source bottom proposed above for UFCs as a consequence of the concentration of some amount of energy in the narrow layer just at the bottom of the source of AKR. The power density up to 100 times higher than that of the simultaneous AKR continuum, would be radiated from a thin vertical layer about ≤ 30 km thick, corresponding to ≤ 40 wavelengths for frequencies around 400 kHz. However, the continuous power supply for such a long-lasting (15 min) compact structure radiating high power and located at the source bottom, remains unclear.

Another possibility (still in the frame of the generation mechanism) corresponds to the narrow-band splitting type structures extensively studied for the Jovian decametric radiation by Leblanc and Rubio (1982). Like Jovian structures, “ridges” are also observed at the upper frequency limits of dynamical spectra, but they neither exhibit a split band characteristic, nor any emission band accompanied by absorption. At all times only single narrow-band emission is present. The significant differences between Jovian and terrestrial auroral conditions should also be taken into account. In a recent paper Shaposhnikov and Zaitsev (1996) explain the narrow-band splitting of Jovian emissions in terms of plasma emissions generated close to the electron density maximum of Jupiter’s ionosphere, heated by strong field-aligned currents connecting Io and Jupiter. For our case we do not see analogous conditions for mechanism to work at relatively elevated heights (400 kHz “ridge” emission level corresponds to about 3800 km above Earth’s surface).

In case of propagation effects ray focusing can be considered. As shown by de Feraudy and Schreiber (1995), a significant effect is possible for rays emitted slightly downwards (up to about 10° with respect to the direction perpendicular to the magnetic field vector) from the source before being reflected upward. However, a persistent narrow band focusing of power density 100 times higher than the simultaneous AKR continuum, lasting for 15 min, when the spacecraft moves over a distance of the order of a thousand kilometres, does not seem possible. As regards to the generation of “ridge” radiation discussed here, no suggestion or explanation can be proposed at the moment.

5 Conclusions

The following conclusions can be drawn from this study:

1. The spectral observations of the sharp upper frequency cutoffs (UFCs) of the AKR, with bandwidth from 4 to 12 kHz are reported here, for the first time to our knowledge.

2. UFCs occurrence is limited to frequencies from 300 to 700 kHz. It corresponds to source bottoms located at low auroral magnetosphere at altitudes around 2100 to 4800 km.

3. From the steepness of UFCs it is suggested that the process of AKR generation is extremely sensitive to the plasma conditions and can abruptly switch on in auroral plasma depletions, when the plasma frequency becomes sufficiently low compared to the gyro-frequency of electrons. It is thus suggested that it can have a non-linear character.

4. Very seldom (<10%) UFCs are accompanied by narrow band “ridges” of the 4 kHz bandwidth (instrumental) at the cutoff frequency. The intensities of the “ridges” can be up to 100 times those of the simultaneous AKR continuum. Their durations are of the order of minutes, up to 15 min.

5. In the search for an explanation of the “ridges” at UFCs three possibilities have been briefly discussed: energy concentration at bottoms of the AKR sources, Jovian-like narrow-band split emissions, and propagation effects. No suggestions can be made about the generation mechanism, but propagation effects seem to be least possible.

6. Bandwidths of the UFCs and “ridges” are comparable with the instrumental profile of POLRAD. For study of their fine structures in more detail an instrument with better time and frequency resolution is needed.

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