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VLF CHARACTERISTICS OF MAGNETIC CUTOFF IN THE CASES OF ULTRARELATIVISTIC ELECTRON PRECIPITATIONS

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Abstract. Continuous, synchronous, many years (1982-1987), on ground registration of VLF signals for short (Aldra-Apatity,) and long (Ragby-Apatity) radio paths has revealed new geophysical phenomena [1-3]. The essence of it is in the ultrarelativistic (E_e ~ 100 MeV) electron precipitation into middle polar atmosphere with synchronous generation by it of X-rays and gamma rays with such intensity that they are capable to produce a sporadic D-layer of conductivity in the middle atmosphere (10 – 40 km of altitude). The effective altitude of such electric conductivity layer may achieve value of 30 km. The time scale of an event is equal to 5 min – several hours, the space scale is equal to one thousand – several thousand km. A crucial item in the proof of electron nature of the events is the existence of the magnetic cutoff in the VLF disturbances**.**

The experimental data for all 129 events for 6 years, represented in this report, are a solid proof of a magnetic cutoff existence in the cases of abnormal VLF disturbances. This fact we declared earlier [1-3], but we publicize the corresponding relatively full volume of experimental data at first.

In all cases of the anomalous VLF disturbances at short radio path they were accompanied by the signal diminishing and signal phase decreasing at the long radio path. At the same time the maximum phase decreasing never prevailed upon the maximum phase decreasing for the short radio path. That may mean only one experimental fact. That the long radio path, which is 3 times longer than the short one, in all cases is only **partly** disturbed in the region of the receiver and that this disturbed part in its length is comparable with the length of the short radio path. So we have the effect of magnetic cutoff relative to the charged particle precipitations.

Once more we attract attention of a reader to the fact [1-3] that an amount of abnormal events per year increased monotonously and significantly from 1982 till 1984 (23, 30, 43 events accordingly) before getting its minimum value in 1985 y (5 events) of Solar activity minimum. Then the amount got values 10 and 19 in 1986 and 1987 years. After one solar cycle (1993- 1996) analog step dependence was gotten by the author of work [4] relatively the relativistic electron fluxes with energy near several MeV.

1. The purpose and the problem putting

A new geophysical phenomena, revealing itself in ultrarelativistic electron precipitation, was discovered on the base of VLF on ground measurements for a short auroral radio path (S_1=885 km) Aldra-Apatity for frequencies f_i = 10.2; 12.1; 13.6 kHz, i = 1, 2, 3. Simultaneously with the registration of signals for the radio trace pointed the Polar Geophysical Institute of RAS fulfilled the measurements of radio signal for a long, partly auroral radio path ($S_2 \approx$ 2497 km) Ragby-Apatity for frequency f_4 = 16 kHz. The experimental data for the last mentioned pass were used earlier [1-3] only qualitatively, i. e. they were used as a proof of existence of the magnetic cut off effect while the processes of charged particle precipitation into the middle polar atmosphere. The purpose of the given publication is a presentation of the quantitative characteristics of the magnetic cut off effect relative to the VLF variations for the long radio trace while all abnormal disturbances, registered at the short radio trace during 6 years from 1982 to 1987.These data are the initial ones for the determination in future the equatorial boundary of the ultrarelativistic electron precipitations at the long radio path.

Comparison of the VLF characteristics for two pointed radio paths is extremely simplified due to "regular" behavior of the VLF signal amplitudes and phases on the both radio paths at the cases of the abnormal disturbances. This regularity reveals itself in the monotonous and qualitatively similar amplitude and phase decreasing of the signals at both passes, in the simultaneous (with an accuracy of some minutes) getting their absolute and relative minimums, if a disturbance is of the recurrence character, and in the monotonous amplitude and phase increasing for all signals at both paths at the recovery disturbance phase. Having in mind that at the short radio path in the abnormal conditions the radio field registered is a sum [5] of the ground diffraction field (the wave of Watson-Fock) and of a ray reflected from above and that at the daytime condition at the long radio path a receiver gets only one normal wave, one may state that a cause of the simultaneous disturbances at both radio paths is mutual and that the extreme values of negative phase and amplitude variations, which take place simultaneously, are the representative characteristics of the abnormal disturbances. So these characteristics are proper for the quantitative comparison of the VLF disturbances at both radio paths. An item, that relatively often at the short radio path for one – three frequencies the phase minimum is late on 3 – 10 minutes relative to the amplitude minimum, is generated partly by the circumstance that the received signal is the sum of constant signal (the ground diffraction wave) and the disturbed "ionosphere" signal. In accordance with the statements made the quantitative comparison of all abnormal VLF disturbances while 6 years (129 events) was fulfilled in the terms of modulus of the maximum negative phase variation and maximum relative amplitude decreasing for all 4 working frequencies (3 frequencies for the short radio path and 1 frequency for the long one) at the moment of disturbance maximum with an accuracy not greater than several minutes.

2. Comparison of the experimental data for a short auroral and a long partly auroral radio paths

All abnormal disturbances registered are divided at 4 classes in accordance to the amplitude variations at the short radio path. The main mechanism of amplitude diminishing of a signal at the short radio path is the compensation of constant ground diffraction field (wave) by first "ionosphere" ray, the amplitude of which is attenuating while a disturbance. The role of the second "ionosphere" ray is negligible. If the amplitudes of one or more radio signals diminish more than 10; 2 and 0.9 times, then an abnormal disturbance is called powerful (Pw), strong (St) and moderate (Md) correspondingly. The other abnormal disturbances are called the weak ones.

Analysis of the powerful disturbances (PwD's)

For 6 years 4 PwD's happened at pure daytime conditions for both radio traces and 2 PwD's in conditions which differed from day time ones. The data which we represent, indicating the dates, the UT beginning time (T_b), the time of disturbance maximum (T_m), the time of disturbance end (T_e), are an amplitude ratio $\eta_i = (A_i(T_m)/A_i(T_b))$ and an absolute value of phase decreasing $\Delta_i = (\varphi_i(T_b) - \varphi_i(T_m))$ for 4 frequencies (i = 1, …, 4) in mcs with an error $\delta = \pm 0{,}5$ mcs. The data for the radio path with frequency f_4 = 16 kHz and the length $S_2 \approx$ 2497 km are marked by solid shrift. The amplitude data were gotten by the help of a channel with an effective band of 20 Hz and the effective bands of the phase channels were much less than 1 Hz [6]. Addressing to the comparison of the experimental data, we point below that the time intervals, which correspond to the conditions different from daytime conditions *at the altitudes more than 60 km for the short radio path*, are marked by solid cursor shrift.

22 April 1984		20 October 1985	
3.20-4.05-7.00 UT		9.45-10.05-11.00	
0.10 ± 0.03	13.5 mcs	0.06 ± 0.05	7 mcs
0.25 ± 0.03	13 mcs	0.17 ± 0.07	9 mcs
0.27 ± 0.06	11 mcs	0.0	8 mcs
0.12 ± 0.07	**11 mcs**	**0.29 ± 0.06**	**6 mcs**

25 March 1986		27 March 1986	
9.00-11.10-13.20 UT		12.35-13.10-19.00	
0.09 ± 0.04	8.5 mcs	0.09 ± 0.04	19.0 mcs
0.12 ± 0.03	10.5 mcs	0.18 ± 0.05	10.5 mcs
0.06 ± 0.07	10.5 mcs	0.0	9.5 mcs
0.07 ± 0.03	**18.5 mcs**	**0.36 ± 0.07**	**9.0 mcs**

2 April 1986		23 April 1986	
16.00-17.25-19.00 UT		18.30-19.15- 20.00	
0.21 ± 0.05	9.0 mcs	0.08 ± 0.04	15.5 mcs
0.31 ± 0.04	8,0 mcs	0.10 ± 0.05	13 mcs
0.0	---	0.0	15.5 mcs
0.36 ± 0.04	**6 mcs**	**0.27 ± 0.05**	**6 mcs**

The most important peculiarities of the PwD's data represented above are the following.

- Maximum decreasing of the phase modulus of a signal at the long S_2 radio path Δ_4 = 18,5 mcs is not greater the analog maximum diminishing Δ_i = 19 mcs (i = 1, 2, 3) for the short radio path with length S_1 = 885 km. This result may mean only one thing. The radio path, which three times longer than the short one, is turned out to be only partly disturbed at all cases, and the length of the North disturbed part of the radio path is comparable with the length of the short radio path. This reason indicates on the effect of magnetic cut off of the particle precipitations relative to the latitude in the cases of abnormal VLF disturbances.
- The second experimental fact is the signal amplitude diminishing in 2.7 – 14 times for the long radio path in daytime conditions, when only one normal wave achieves a receiver and the pointed diminishing of the signal is proportional to the diminishing of the normal wave amplitude. This diminishing is caused by two reasons: by the width compression of the wave guide at the North terminal and by an appearance of abnormal conductivity in the middle atmosphere of the disturbed part of the wave guide.

Analysis of the strong disturbances (StD's)

Having discussed the PwD's, now we address to the StD's. During 6 years 17, 20, 24, 3 (1985 y.), 3 and 15 such abnormal disturbances took place per a year correspondingly. The 1985 y. was a year of minimum Sun activity. Omitting the experimental data tables, we present the results of their analysis.

According to the StD's for 1982 y. one has again that the maximum values Δ_4 = 7.5 mcs for the day time conditions and 9.5 mcs for other conditions were less than the corresponding values Δ_i = 14 mcs and 15 mcs. The amplitude diminishing of the normal wave in the daytime for the long radio path was characterized by the values $\eta_4 = 0.27 \div 0.84$.

According to the StD's for 1983 y. one has:

- The maximum value Δ_4 = 16 mcs at daytime conditions was less than the maximum value Δ_i = 18 mcs;
- The normal wave amplitude diminishing for the long radio path was characterized by the values $\eta_4 = 0.10 \div 0.92$.

The analog results for 1984 y. data are the following:

- The maximum value Δ_4 = 9.5 mcs for all conditions of lighting at the radio path and the maximum value Δ_i = 13 mcs at daytime and 17 mcs at night;
- η_4 = 0.07 ÷ 0.83.

The StD's for 1985-86 years were rare, so they all are represented below:

27 September 1985
23.30-23.50-24.20 UT

0.43 ± 0.06	8 mcs
0.59 ± 0.03	7 mcs
0.67 ± 0.03	6 mcs
0.55 ± 0.14	**0 mcs**

23 October 1985
8.50-09.05-10.50

0.36 ± 0.04	12 mcs
0.53 ± 0.05	7 mcs
0.46 ± 0.06	6.5 mcs
0.58 ± 0.05	**5.5 mcs**

24 October 1985
21.00-22.15-25.00 UT

0.22 ± 0.05	14 mcs
0.36 ± 0.03	15.5 mcs
0.60 ± 0.03	18.5 mcs
0.59 ± 0.22	**----**

2 April 1986
15.50-16.25-19.00

0.21 ± 0.05	8,0 mcs
0.29 ± 0.04	8.0 mcs
0.13 ± 0.13	8.5 mcs
0.39 ± 0.04	**4.5 mcs**

3 April 1986
6.30-7.45-9.00 UT

0.24 ± 0.05	8 mcs
0.52 ± 0.07	8.5 mcs
0.46 ± 0.12	7 mcs
0.54 ± 0.05	**5 mcs**

24 April 1986
14.05-14.30-15.40

0.20 ± 0.04	11.0 mcs
0.44 ± 0.06	9.5 mcs
0.21 ± 0.03	9 mcs
0.56 ± 0.05	**7 mcs**

24 April 1986
14.05-16.30-15.40 UT

0.24 ± 0.06	5.5 mcs
0.71 ± 0.05	4 mcs
0.60 ± 0.20	4 mcs
0.76 ± 0.05	**3 mcs**

According to these 6 disturbances data for 2 years one sees that they do not contradict to the conclusions made above.

In 1987 y. the number of the events increased to 15:

12 May 1987
10.40-10.55-(?) UT

0.43 ± 0.05	8.5 mcs
0.53 ± 0.04	7.0 mcs
0.62 ± 0.03	6.5 mcs
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12 May 1987
20.15-21.10-22.30

0.45 ± 0.07	11 mcs
0.31 ± 0.02	8.0 mcs
0.33 ± 0.03	6.0 mcs
0.30 ± 0.05	**8 mcs**

13 May 1987
16.30-17.05-18.30 UT

0.33 ± 0.04	11 mcs
0.41 ± 0.04	8.5 mcs
0.54 ± 0.03	8.0 mcs
0.54 ± 0.11	**8 ± 1 mcs**

19 May 1987
20.20-20.50-21.00

0.15 ± 0.03	9.5 mcs
0.31 ± 0.03	10.0 mcs
0.33 ± 0.04	9.0 mcs
0.47 ± 0.10	**9.5 ± 1 mcs**

20 May 1987
22.40-23.10- 23.20 UT

0.45 ± 0.06	11.0 mcs
0.58 ± 0.04	9.0 mcs
0.55 ± 0.05	9.0 mcs
0.73 ± 011	**7.0 mcs**

23 May 1987
6.10-6.30-7.00

0.48 ± 0.03	7.5 mcs
0.59 ± 0.03	6.5 mcs
0.61 ± 0.03	6.0 mcs
0.64 ± 0.05	**5.0 mcs**

6 June 1987
10.25-10.45-10.55 UT

0.32 ± 0.04	3.5 mcs
0.53 ± 0.12	5.0 mcs
0.51 ± 0.05	5.0 mcs
0.59 ± 0.09	**5.5 mcs**

8 June 1987
4.30-5.25-6.25

0.31 ± 0.02	14.5 mcs
0.42 ± 0.02	11.5 mcs
0.51 ± 0.05	12.0 mcs
0.59 ± 0.05	**16.5 mcs**

11 June 1987
0.30-1.05-(?) UT

0.44 ± 0.04	7.0 mcs
0.53 ± 0.03	7.0 mcs
0.57 ± 0.07	6.5 mcs
0.53 ± 0.05	**12.0 mcs**

28 June 1987
3.15- 5.00- 7.00

0.60 ± 0.06	17.5 mcs
0.45 ± 0.03	15.0 mcs
0.39 ± 0.02	14.0 mcs
0.39 ± 0.06	**17.5 mcs**

29 June 1987
8.30-9.40-11.00 UT

0.42 ± 0.05	13.0 mcs
0.47 ± 0.05	11.0 mcs
0.56 ± 0.05	11.0 mcs
0.73 ± 022	**5.0 mcs**

10 July 1987
0.10-2.00-6.00

0.20 ± 0.04	9.5 mcs
0.23 ± 0.02	10.0 mcs
0.30 ± 0.02	10.5 mcs
0.23 ± 0.23	**---**

10 July 1987
7.00- 7.40- 8.30 UT

0.45 ± 0.03	8.5 mcs
0.56 ± 0.04	6.5 mcs
0.57 ± 0.02	6.5 mcs
0.69 ± 0.4	**2 mcs**

18 September 1987
15.30-15.35-15.50

0.27 ± 0.05	5 mcs
0.36 ± 0.03	7 mcs
0.42 ± 0.04	5 mcs
0.49 ± 0.04	**10.5 mcs**

31 October 1987
9.50-10.10-10.40 UT

0.27 ± 0.02	3 mcs
0.46 ± 0.03	8 mcs
0.57 ± 0.03	3 mcs
0.68 ± 0.06	**4.5 mcs**

According to these date one has for the daytime conditions:

- $\Delta_4 = \Delta_i$ = 17.5 mcs;
- η_4 = 0.23 – 0.73.

Analysis of the moderate disturbances (MdD's)

Let us discuss the MdD's, which are weaker than the StD's, but are significant in comparison to the apparatus errors. While 6 year there were 6, 10, 18, 1 (1985 y.), 1 and 4 abnormal disturbances per year correspondingly. Below we represent all the data for 1984 y.

12 April 1984
16.00-16.10-18.00 UT

0.89 ± 0.05	11 mcs
0.83 ± 0.04	9.5 mcs
0.80 ± 0.07	10.5 mcs
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23 April 1984
4.40-4.55-5.50

0.60 ± 0.04	5 mcs
0.81 ± 0.09	3.5 mcs
0.95 ± 0.10	9 mcs
0.88 ± 0.06	**2 mcs**

5 May 1984
4.40-5.20-5.50 UT

0.65 ± 0.08	3 mcs
0.69 ± 0.06	3 mcs
0.67 ± 0.07	5 mcs
0.73 ± 0.05	**2 mcs**

23 May 1984
23.25-23.30-24.30

0.53 ± 0.05	4 mcs
0.68 ± 0.04	5 mcs
0.74 ± 0.08	4 mcs
0.70 ± 0.2	**7 mcs**

24 May 1984
14.20-15.10-16.30 UT

0.69 ± 0.04	5.5 mcs
0.91 ± 0.04	4.5 mcs
0.82 ± 0.08	3 mcs
0.86 ± 0.06	**6.5 mcs**

9 June 1984
20.45-21.00-22.50

0.63 ± 0.04	9 mcs
0.58 ± 0.05	7.5 mcs
0.71 ± 0.04	7 mcs
---	**---**

10 June 1984
10.05-10.25-11.00 UT

0.52 ± 0.04	8 mcs
0.58 ± 0.05	9 mcs
0.67 ± 0.05	7 mcs
0.77 ± 0.35	**---**

12 June 1984
9.10-9.30-10.00

0.75 ± 0.04	4 mcs
0.93 ± 0.09	4 mcs
0.93 ± 0.07	3 mcs
---	**---**

25 June 1984
6.50-7.30-8.40 UT

0.58 ± 0.05	7.5 mcs
0.65 ± 0.04	6.5 mcs
0.75 ± 0.05	4 mcs
0.77 ± 0.04	**4 mcs**

26 June 1984
2.30-2.40-6.00

0.71 ± 0.06	4.5 mcs
0.60 ± 0.06	4 mcs
0.71 ± 0.07	5.5 mcs
0.75 ± 0.2	**3 mcs**

1 July 1984
22.15-22.30-26.00 UT

0.72 ± 0.06	2 mcs
0.78 ± 0.06	3.5 mcs
0.82 ± 0.06	3 mcs
0.84 ± 0.04	**1 mcs**

2 July 1984
7.25-7.40-9.00

0.88 ± 0.05	6 mcs
0.67 ± 0.05	5 mcs
0.72 ± 0.05	5 mcs
0.86 ± 0.06	**4 mcs**

2 July 1984
17.30-17.50-18.10 UT

0.89 ± 0.05	5 mcs
0.72 ± 0.05	5 mcs
0.74 ± 0.06	4.5 mcs
0.81 ± 0.07	**3 mcs**

4 July 1984
20.00-20.20-21.15

0.60 ± 0.04	8 mcs
0.65 ± 0.06	6 mcs
0.70 ± 0.05	6 mcs
0.80 ± 0.04	**3 mcs**

5 July 1984
18.45-19.05-20.30 UT

0.62 ± 0.06	4.5 mcs
0.70 ± 0.08	4 mcs
0.76 ± 0.06	3 mcs
0.87 ± 0.04	**2 mcs**

18 July 1984
18.10-18.20-18.40

0.56 ± 0.06	1 mcs
0.63 ± 0.06	5 mcs
0.65 ± 0.06	3.5 mcs
0.76 ± 0.14	**2.5 mcs**

19 July 1984
22.10-22.20-22.30 UT

0.54 ± 0.05	---
0.69 ± 0.07	---
0.78 ± 0.06	---
0.84 ± 0.04	**---**

19 September 1984
15.40-16.05-___

0.73 ± 0.06	8.5 mcs
0.68 ± 0.06	5 mcs
0.71 ± 0.07	5 mcs
0.88 ± 0.06	**4 mcs**

According to these data it is possible to state the following for the day conditions:

- The maximum value Δ_4 = 6.5 mcs is less than the maximum value Δ_i = 11 mcs**;**
- $\eta_4 = 0.70 \div 0.88$.

Omitting the MdD's data for another 5 years, let us compare the maximum values of the phases and the value intervals for η_4:

- In 1982 y ~ (Δ_4 = 2,5 mcs) < Δ_i = 6 mcs and $\eta_4 = 0.76 \div 0.92$;
- In 1983 y ~ (Δ_4 = 6 mcs) < Δ_i = 8 mcs and $\eta_4 = 0.46 \div 0.86$;
- For a singular disturbance in 1985 y ~ (Δ_4 = 5 mcs) < Δ_i = 8.5 mcs, $\eta_4 = 0.74$;
- For a singular disturbance in 1986 y ~ (Δ_4 = 1 mcs) < Δ_i = 4 mcs, $\eta_4 = 0.84$;
- For 4 disturbances in 1987 y ~ (Δ_4 = 5 mcs) < Δ_i = 7 mcs, $\eta_4 = 0.66 \div 0.78$.

Appreciating the data represented above it is useful to compare them with the following computed values. According to the computation the values of the phase of the first ionosphere ray for the short radio path with S_1=885 km and with the frequencies f_i = 10.2; 12.1; 13.6 diminish on 1.0 *rad.* (16 mcs), 1.3 *rad.* (17 mcs), 1,5 *rad.* (18 mcs) correspondingly, if the effective wave guide height diminishes from 60 km to 40 km. The phase values decrease on 1.3 *rad.* (21 mcs), 1.7 *rad* (22 mcs), 2.0 *rad.* (24 mcs), if the effective height of a wave guide becomes lower on 30 km. According to the calculations the phase of a signal with frequency f_4 = 16 kHz and for a long radio path with S = 3000 km [7] is estimated as 2.3 *rad.* (23 mcs) due to the changing of light conditions.

3. Conclusion and discussion

The above experimental data represented are a solid proof 1) of a mutual physical cause of VLF-disturbances on a short auroral and on a long partly auroral radio paths with a mutual receiving point and 2) of a magnetic cut off effect existence relative to latitude in the cases of abnormal VLF disturbances caused by the ultrarelativistic electron precipitations. The South boundary of an electron precipitation is controlled by the Earth magnetic field. That is disclosed by the fact of disturbance only of the North part of long radio path. The data represented will permit to solve a new inverse VLF problem relative to determination of the equatorial verge of a precipitation zone at the long radio path. Such usage of the data is especially useful after the end of existence (in the 90-th years) of VLF generating station in Aldra with the working frequencies used in this work. It is impossible to predict when the satellite measurements will solve this problem relative to the ultrarelativistic electrons with energy of several hundred MeV. These electrons are ultrarelativistic in the sense that they, penetrating into middle atmosphere at an altitude near 40 km, generate the bremsstrahlung X-rays and gamma rays, the intensity of which is enough for creation of a sporadic D-layer of conductivity at the altitudes 10 – 40 km.

About the effect of magnetic cut off we declared earlier [1-3] but publicize the corresponding relatively full volume of experimental data at first. Once more we attract attention of a reader to that, that an amount of the abnormal events per year increased monotonously and significantly from 1982 till 1984 before getting the minimum value at the year of solar activity minimum 1985 y.

At the end we add that a source of ultrarelativistic electrons is unknown. But the fact, that most of the abnormal VLF disturbances have taken place at daytime, as it was shown above by the table data, induce us to think that Sun is the main pretender on this role.

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